JOURNAL OF

Petroleum Technology

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- Displacement Tests in a Consolidated Porous System

MARCH, 1954

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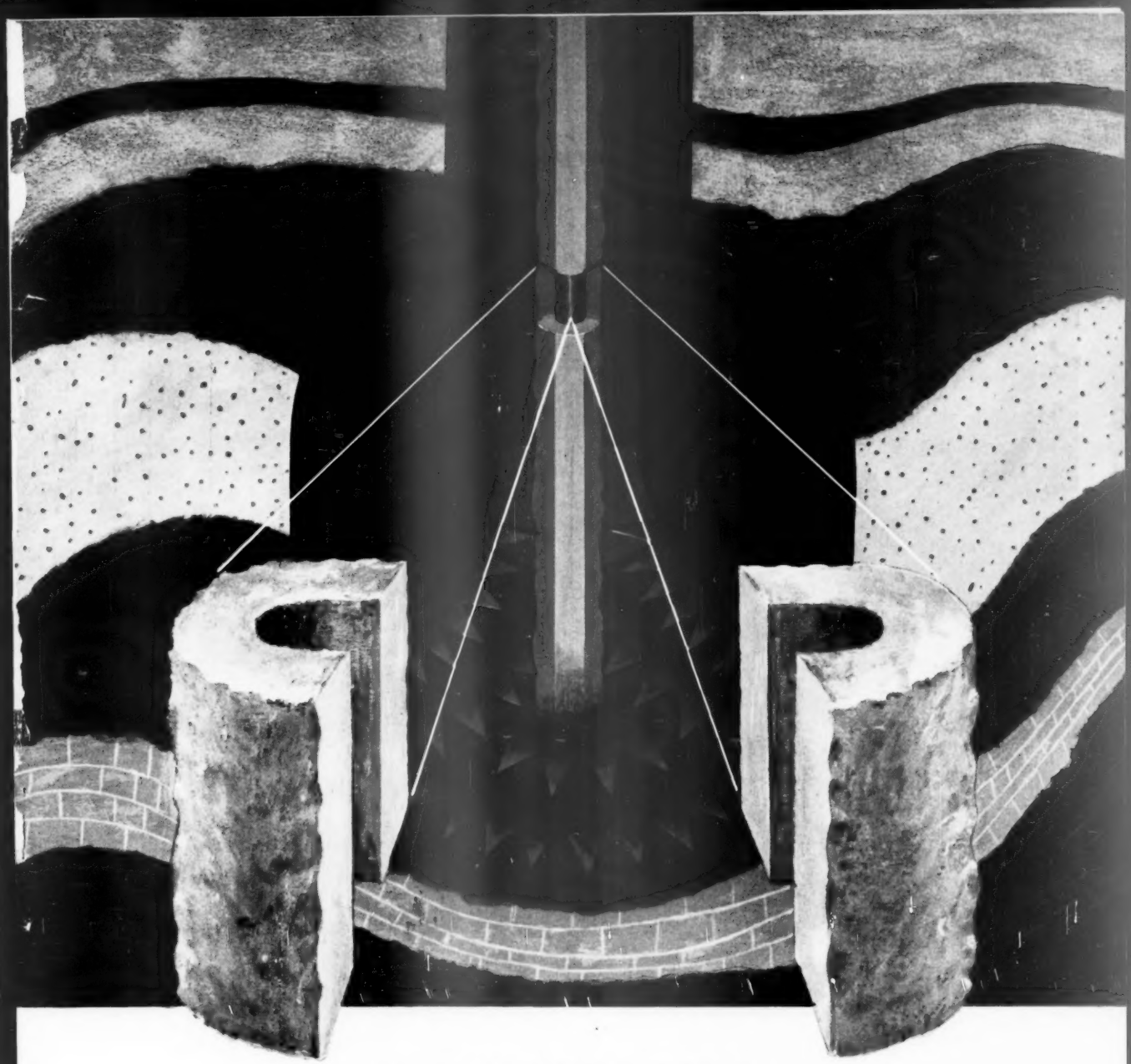

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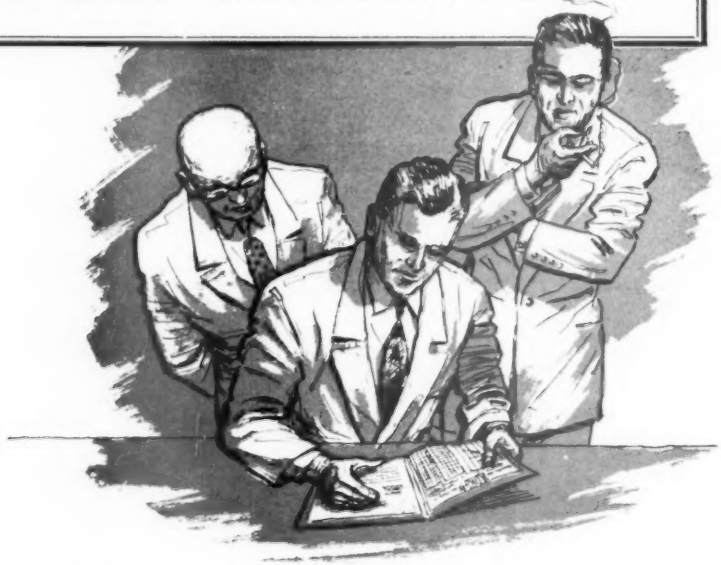

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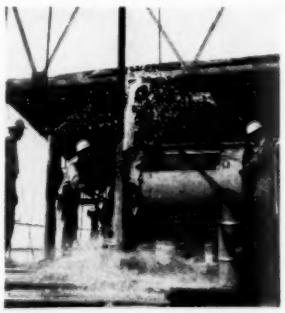
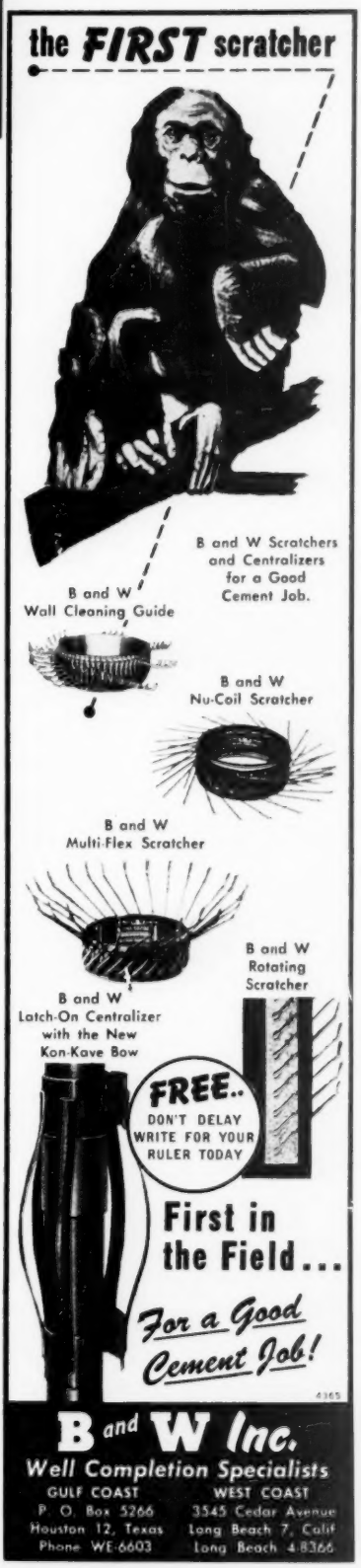


Photo by Humble Oil and Refining Co.

ON THE COVER

Salt water gushes from a formation far beneath the surface as a drill-stem test is made on a wildcat well. This is one of the most exciting moments in the oil patch, when the type of fluid that has entered the drillstem during the test is revealed. Also, it is a moment of carefulness for the roughneck, who tries to avoid being drenched by the spurting liquid.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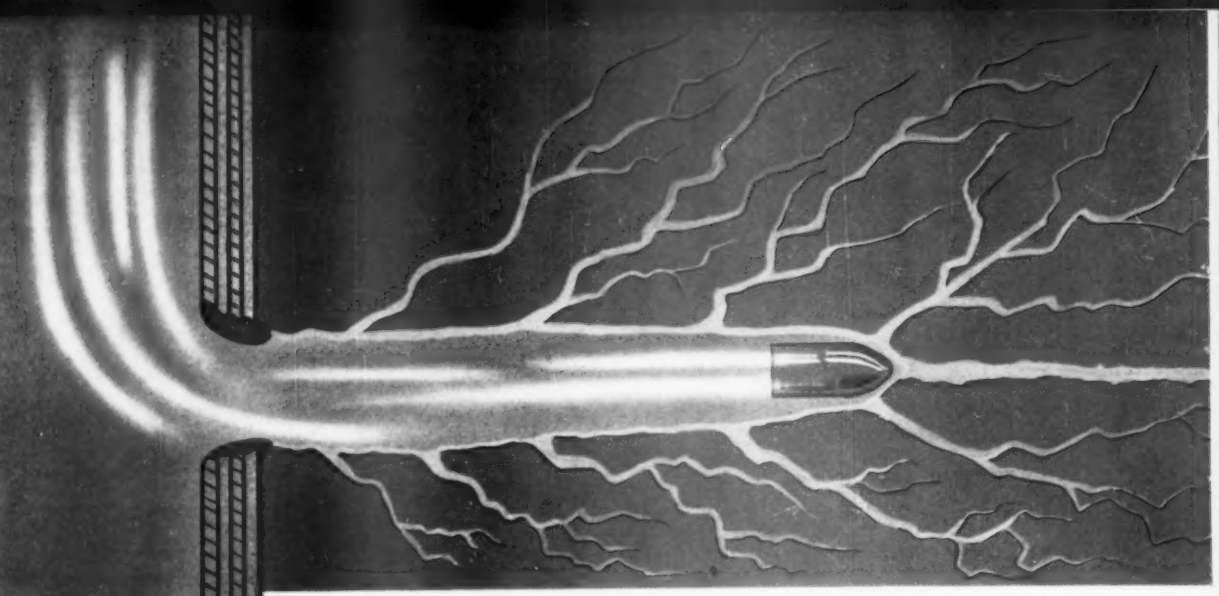

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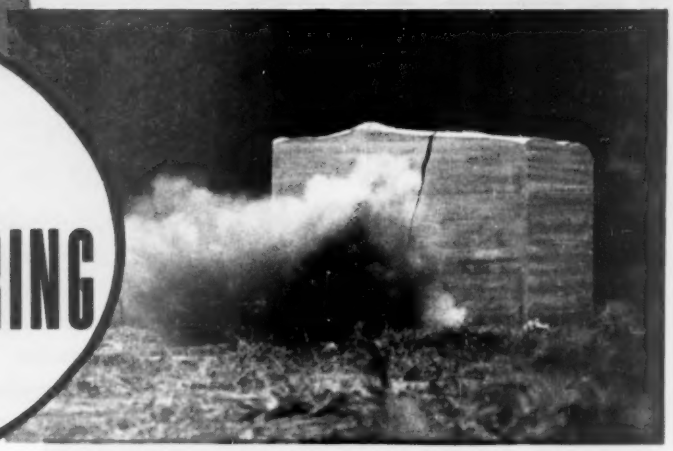

■ Thirty-thousand-pound block of aged concrete serves as target for missile of Formation Fracturing Tool. Notice fissure opening one millisecond after explosion.

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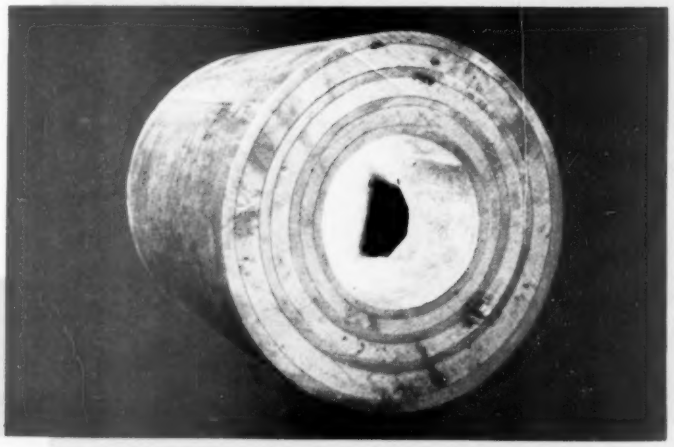

■ Another test shows clean, 2-inch hole through four strings of casing and cement. No burrs or interior casing damage remain after firing.

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The well completed was in an old field where the zones are very thin and many of the sands produce 100% water. An error of a very few feet in measurements means the difference between success or failure. Ran the McCullough Radiation Well Logger with Scintillometer and simultaneously recorded a collar log. Collar locations checked within 6" at 3600'.

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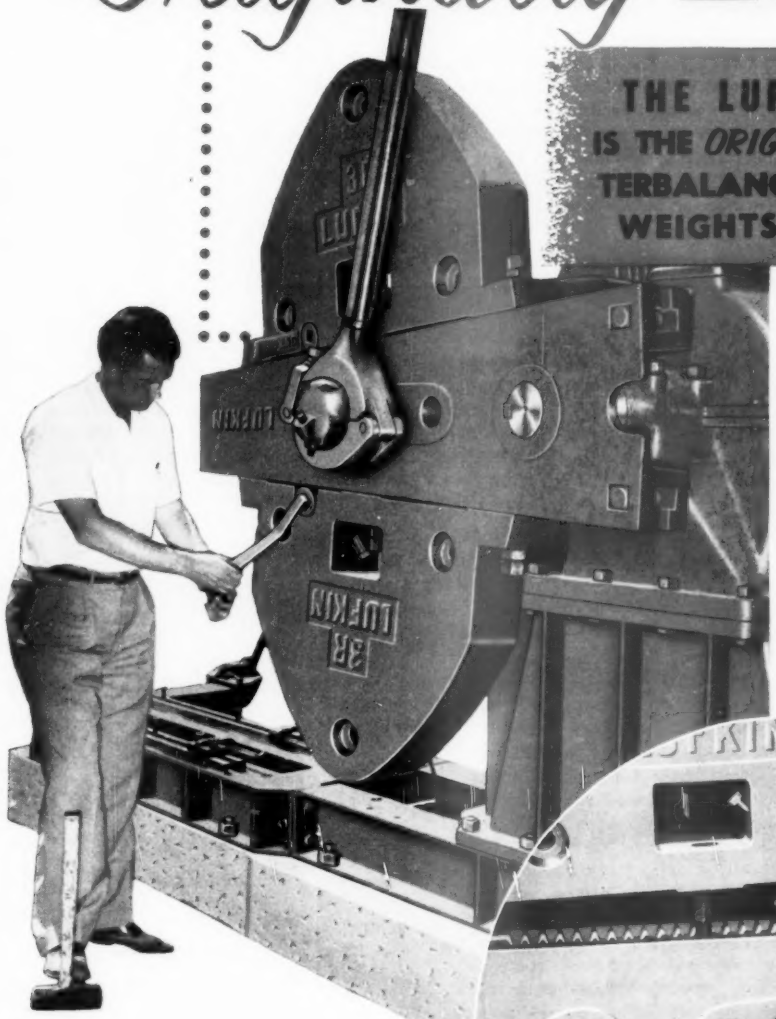

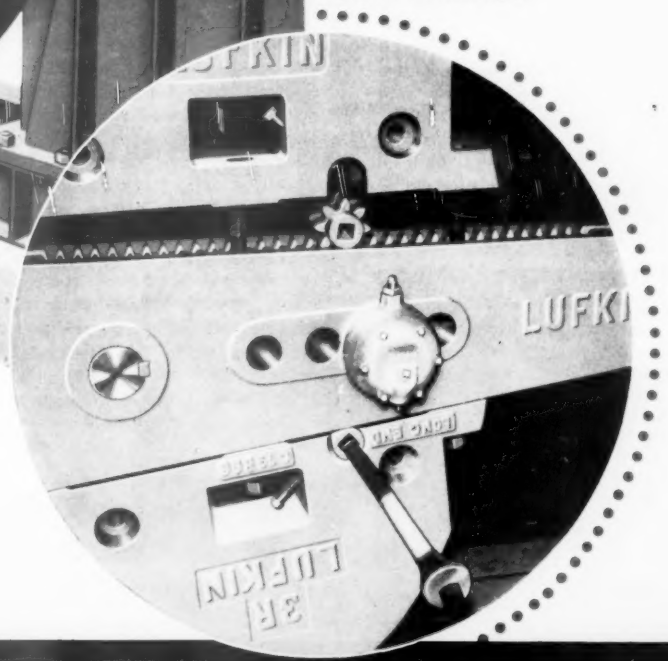

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The features of design and construction which ensure success of the Baker Triplex Cementing Shoe are all "time proven" Baker principles. The Baker "Whirler" principle has proved to be far superior to undirected jetting action, which often fails to prevent cement channeling, and may wash out dangerous cavities with resultant contamination of the cement slurry.

STRONG SAFE CONSTRUCTION

The accompanying illustrations show how the full strength of the Triplex Cementing Shoe has been retained. There are no thin walls or elongated slots to weaken the shoe, and the operating mechanism is both sturdy and simple; see Fig. 1.

The Triplex Baffle Collar (Product No. 137 M&F, Fig. 2) stops the cementing plug a joint or two above the Triplex Shoe, thus retaining any cement tailings inside the casing and permitting only cement slurry of specified consistency to pass out the shoe.

The Triplex Float Collar, with spring-loaded flapper valve (Product No. 134 M&F, Fig. 3) likewise can be used as a stop for the cementing plug and provides an additional float valve in the casing.

POSITIVE BACK-PRESSURE VALVE

The spring-loaded flapper valve in Baker Triplex Cementing Shoes provides another important safety feature. While guiding and floating the casing, and when washing or conditioning the hole preparatory to cementing, the Baker Triplex Cementing Shoe operates as a conventional float shoe. The instant pump pressure is stopped, this flapper valve closes, and thereafter—even though leaks may develop in the casing or in the surface equipment—the *cement is held in place behind the casing until it sets.*

"CENTRALIZED" CASING ASSISTS OPERATION

By mounting Baker Casing Centralizers at suitable intervals above the Triplex Shoe throughout the zone to be cemented, the "centralized" casing presents a uniform annulus for placement of an effective sheath of cement. A Baker Casing Centralizer mounted immediately above the Triplex Shoe serves to center the Metal Petal Basket so that it expands uniformly against the wall of the hole, thus increasing its bridging effectiveness.

OPERATION OF METAL PETAL BASKET

The Baker Metal Petal Basket is attached to the Triplex Shoe in a manner that prevents it from being damaged during rotation or other movement of the casing. After the Basket has been released, the casing can be rotated without damaging the Basket. Figure 4 shows details of construction of the "Metal Petal" Basket which consists of a number of individual petals made of flexible sheet metal. These petals are mounted on reinforcing ribs, which in turn are mounted on a ring. The petals overlap each other (either in closed or expanded position) by sufficient margin to prevent cement slurry above the Basket from passing to the formation below.

After the hole has been washed and conditioned, the Baker Triplex Cementing Shoe is positioned at the desired cementing point and made operative as described on the opposite page.

The Baker Metal Petal Basket then expands to form a bridge even in large-diameter holes—readily conforming to hole irregularities over a wide range of diameters—and *retains the cement slurry above the Basket.* Lower, permeable, low-pressure zones are thus protected from contamination by the cement slurry.

GOOD "FIRST-TIME" CEMENT JOB

With the Basket expanded, forming a bridge at this point, cementing is commenced with the slurry being "whirled" upward around the "centralized " casing. Danger of channeling is practically eliminated, and by "whirling" (not jetting) the slurry, the possibility of washing out cavities is minimized.

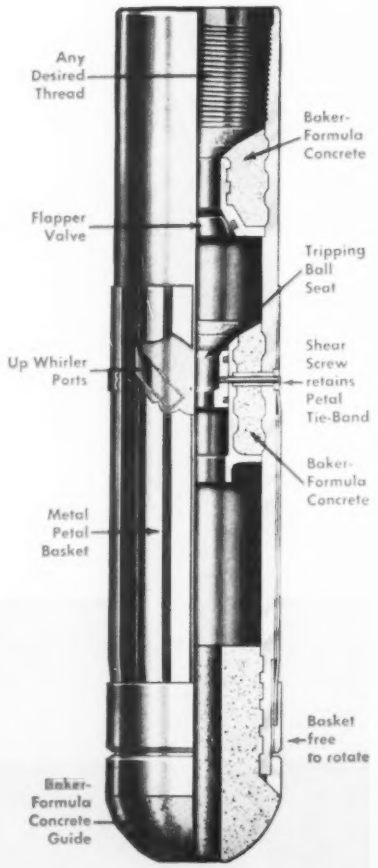


Fig. 1—Baker Triplex Cementing Shoe

Fig. 4—Detail of Baker Metal Petal Basket

Fig. 3—Baker Male and Female Triplex Flapper Valve Float Collar

Fig. 2—Baker Male and Female Triplex Cement Baffle Collar

a good "FIRST TIME" CEMENT JOB

while protecting permeable, low-pressure zones below from cement contamination

HERE'S HOW THE TRIPLEX SHOE OPERATES

A A Baker M&F Cement Baffle Collar is installed a joint or two above the Triplex Shoe to stop the cementing plug so that cement tailings are retained *inside* the casing, or a Baker M&F Cement Flapper Valve Collar can be used where an additional float valve is desired.

B Baker Casing Centralizers are installed on, and above, the shoe joint to center the casing and provide a uniform annulus to receive the cement slurry.

C A Hold-Down Strap (secured by shear screws) retains the Baker Metal Petal Basket close against the Triplex Shoe while running-in the casing and conditioning the hole.

D Cementing Ports are covered by the Tripping Valve until cementing is commenced.

E A spring-loaded Flapper Valve permits passage of the cement slurry through the Triplex Shoe, but closes instantly to prevent any return flow of the slurry.

F After reaching the desired point in the hole, circulation is established through the ample central passageway. A Tripping Ball is now pumped (or allowed to gravitate) downhole to seat upon Tripping Valve and prevent circulation through the Shoe. Pressure of 400-500 psi is applied to the casing to shear the Tripping Valve Shear Screws and force the Tripping Valve downward to expose the cementing ports.

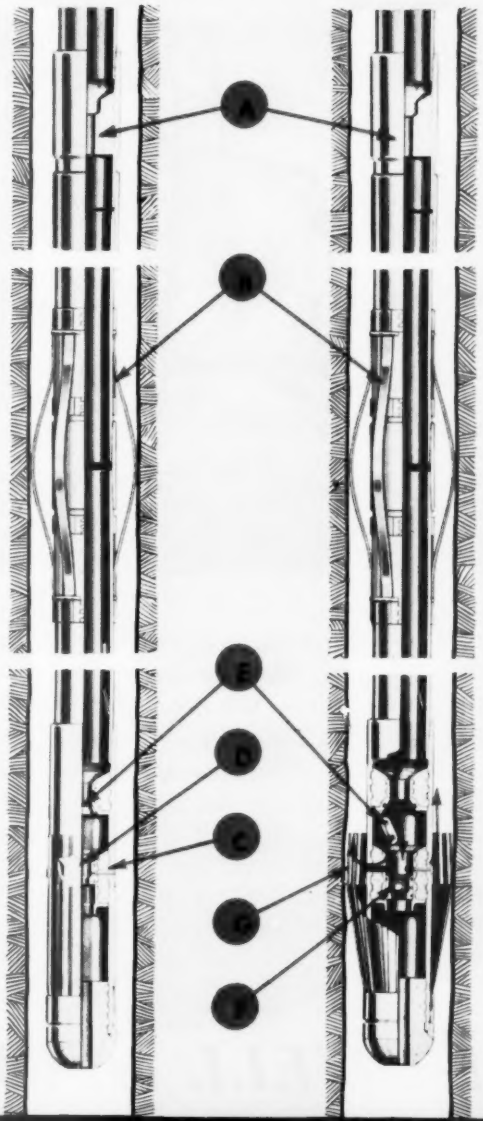
G Shearing these screws also releases the Basket Hold-Down Strap and allows the Metal Petal Basket to expand outwardly against the wall of the hole. The Basket has a wide range of expansion and forms a bridge in large-diameter or irregularly-shaped holes far beyond the range of a rubber packing element.

SUCCESSFUL CEMENTING FOLLOWS

The cementing operation is now carried out in the conventional manner with the cement slurry directed upward with the exclusive Baker "Whirling" action.

EASILY DRILLED OUT

Only readily drillable materials are used for all internal parts of the Baker Triplex Cementing Shoe; and two, one-half inch set screws hold the inner assembly stationary to facilitate drilling out.



CONTACT any Baker representative or office for complete details as well as specific recommendations for using Baker Triplex Cementing Shoes.

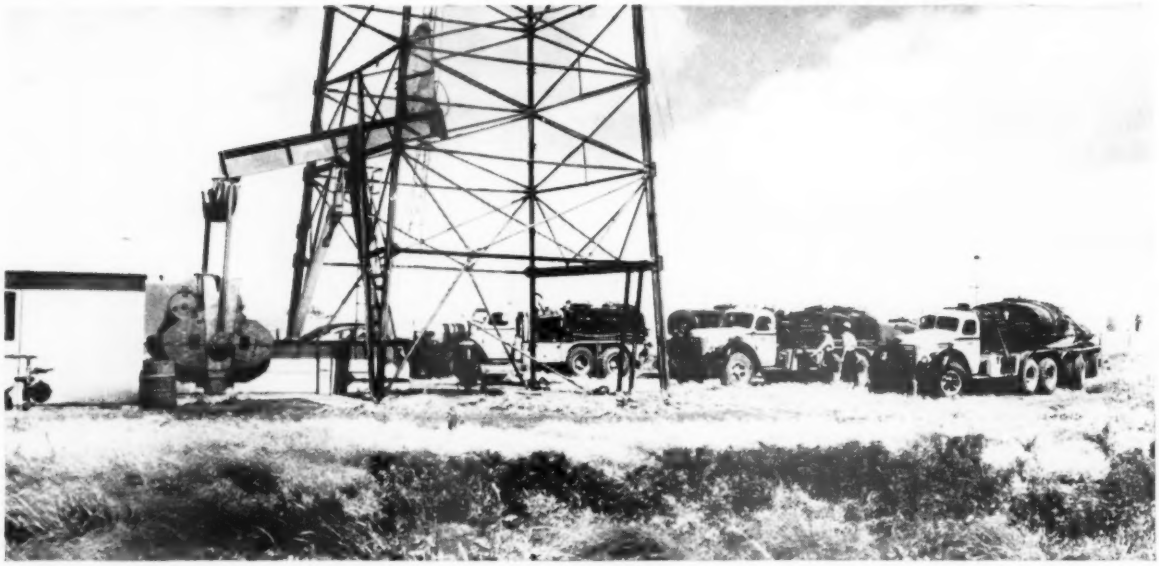
BAKER OIL TOOLS, INC.
HOUSTON · LOS ANGELES · NEW YORK

BAKER *Triplex*

CEMENTING SHOE

PRODUCTION INCREASED FROM 60 TO 450 BOPD WITH XM ACID

DOWELL XM Acid treatment boosted production after ordinary acid failed to improve flow



This new oil well had been completed in a dolomitic limestone formation. Ordinary acid had failed to improve production from this and neighboring wells. A trace of emulsion and incomplete return of the spent acid suggested that effective permeability had been reduced by swollen silicates plugging the pore spaces.

The operator decided to employ a Dowell treatment using XM Acid to control silicate swelling and increase production. As a result, production went from 60 to 450 BOPD and the XM Acid treatment resulted in a quick kick-off and clean-up for the operator.

Other Dowell addition agents are designed to remove mud from producing formations; to speed reaction rate; to increase penetrating ability; to increase wetting ability and prevent emulsions; to remove "gyp"; to trace fluid movement; to increase acid weight.

For more information on Dowell addition agents and the many oilfield services and products offered by Dowell, call the nearest office. Or write directly to Tulsa, Dept. C-15.

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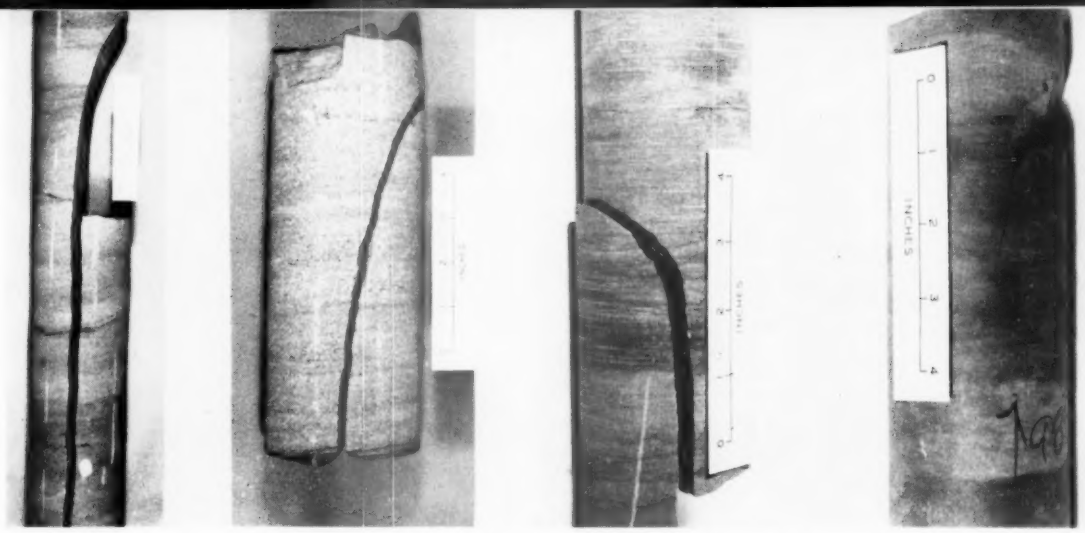


FIG. 1 — TYPICAL DRILLING-INDUCED FRACTURES

Fractures Induced During Drilling

By Charles Pendexter and Richard E. Rohn

The Carter Oil Co., Tulsa, Okla.

Introduction

In the study of fractured reservoirs it is essential to know the extent to which the fractures contribute to the porosity and permeabiilty of the reservoir. The amount of fracture porosity can be determined by measuring the dimensions and abundance of fractures in cores brought to the surface. Therefore, it is necessary to know if the fractures in the core are representative of those originally present in the reservoir.

During the examination of fractured cores from many areas the existence of artificially induced fractures has been established. Induced fractures are those formed during drilling operations and may be present in the strata adjacent to the well bore as well as in the recovered core.

Criteria by Which Induced Fractures May be Recognized

Fractures formed in the cores during drilling can be recognized by the following criteria, which have been determined by examination of a large number of fractured cores:

1. There is no mineralization or hydrocarbon residue on the fracture surface.

2. In broken cores the halves may be fitted back together tightly, the edges of the core at the fracture edge matching without overlap of either half of the core.

3. Induced fractures usually curve abruptly into the center of the core in a down-the-hole direction as illustrated in Fig. 1. In the majority of the cases where the base of the fracture could be observed, the fracture ended at a change in lithology.

4. Induced fractures generally split a core into equal halves.

5. Induced fractures often show a slight rotation about the core axis.

In cores from three fracture producing zones approximately 50 per cent of all observed fractures are characterized by these features. Such fractures have been found in all stages of development, ranging from only the upper sloping part a few inches in length to fractures several feet long. On the basis of these observations it is believed the the differentiation of induced fractures from natural fractures is possible in most areas.

(Continued on Page 49)

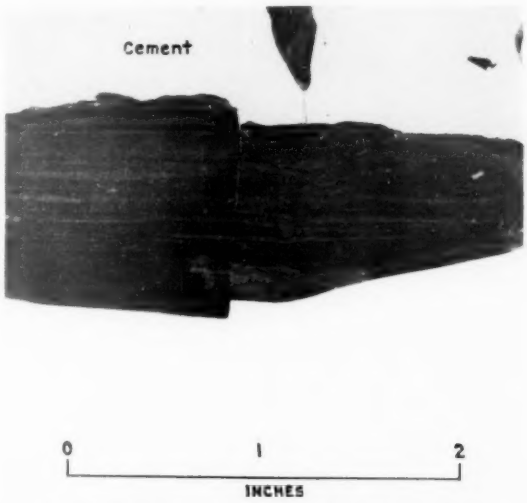
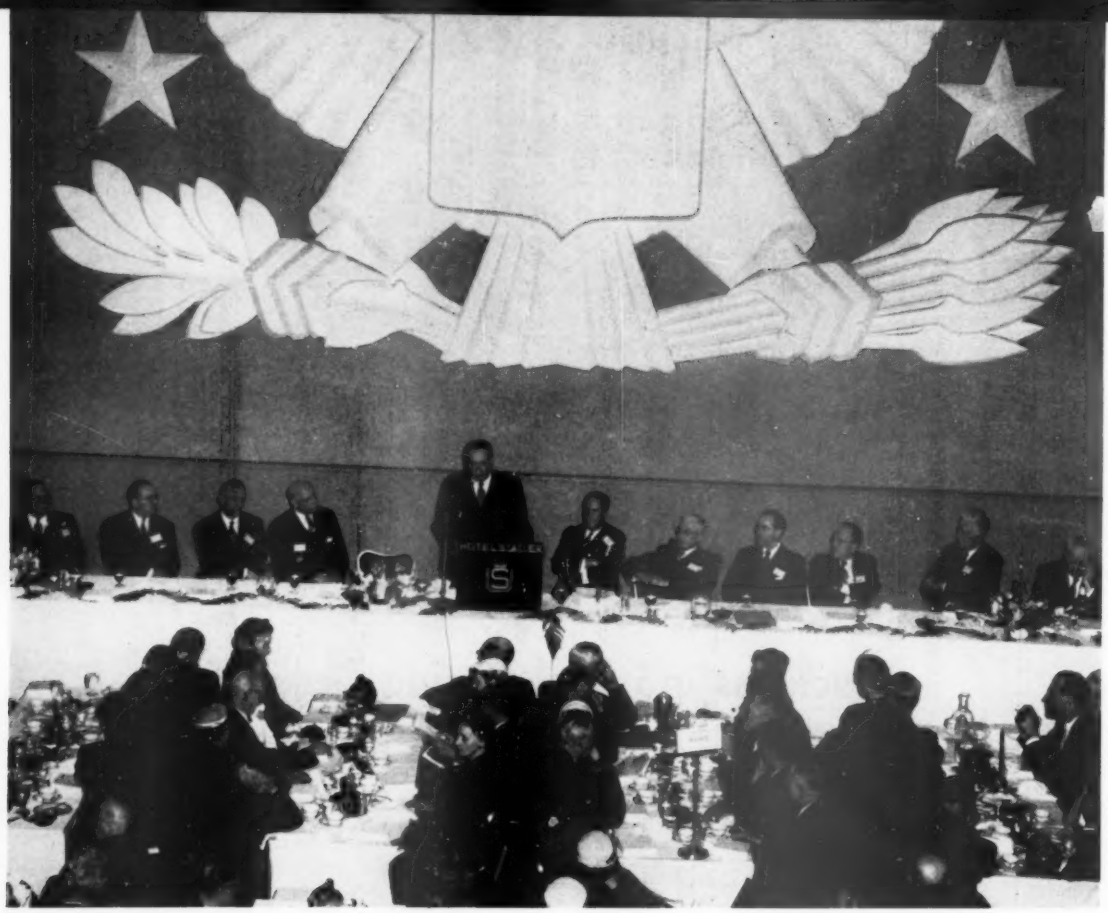


FIG. 2 — DRILLING-INDUCED FRACTURE WHICH FORMED AHEAD OF THE BIT.



Grayson Kirk, president of Columbia University, speaks at the Welcoming Luncheon.

Claude R. Hocott, Frank M. Porter, and John R. McMillan.

Registrants Total 3,800 For Annual AIME Meeting

Approximately 150 Petroleum Branch members were among the 3,800 men and women registered for the 176th Annual Meeting of the AIME, held in New York last month. This petroleum attendance was slightly higher than for past New York meetings.

The Petroleum Branch Dinner on Tuesday evening, Feb. 16, drew a crowd of 165, larger than normal, to hear Frank M. Porter, president of the API, speak.

John R. McMillan assumed leadership of the Petroleum Branch from Claude R. Hocott at this dinner. Leo F. Reinartz became Institute president the following night at the Annual Banquet, succeeding Andrew Fletcher.

The South Plains Local Section was awarded the banner given yearly to the section of the entire Institute having the largest per cent gain in membership. M. C. Gulledge of Magnolia, Brownfield, Tex., accepted the award at the Institute Welcoming Luncheon.

The technical program for the Petroleum Branch, which consisted of 10 papers, was well received.

The report of the Production Review Committee, given by R. B. Gilmore, chairman, A. H. Chapman, Milton Williams, and E. W. Shaw, drew a large attendance. This comprehensive report is available free of charge from the Dallas Office to AIME members (see advertisement elsewhere in this isue).

Petroleum Branch Affairs ... as interpreted by JOE B. ALFORD Executive Secretary, Petroleum Branch

Local Section Appropriations for 1954

A problem that has concerned the AIME Board of Directors, the AIME Council of Section Delegates, and many of the local sections themselves during the past year has been the matter of appropriations to local sections. Appropriations to sections were granted initially by the Institute to assist some of the sections that had financial difficulties, but during the past few years the appropriations have become a matter of standard procedure in the operation of most sections. The philosophy of making appropriations from the Institute headquarters to the sections has been a highly controversial issue — some members object to it strongly. However, the idea has prevailed that if appropriations were to be granted, any section ought to be entitled to them as any other, with the net result that the entire matter had become a problem of major proportions.

The AIME Council of Section Delegates devoted a good part of its all-day session on February 13 at the recent AIME Annual Meeting to the subject. Many of the sections would favor the discontinuance of appropriations from the Institute altogether, if the Institute dues could be lowered by a like amount. However, such sections take the position that if appropriations are to be made, they should be granted on some equitable basis that is fair to all groups, such as a given amount per member. This resulted in a Council of Section Delegates recommending to the AIME Board of Directors that each local section be granted a refund of $1.00 for each member residing in its territory. This was accompanied by a recommendation that a portion of the initiation fee of new members be refunded to the sections also. The Board took the matter under study and then acted on the recommendations in a later session. The final result is that appropriations to local sections in 1954 will be made as follows:

1. *Fifty cents per member:* Each local section will be refunded 50 cents for each paid-up member in its territory. The date on which the section membership will be taken for the purpose of figuring the refunds has not yet been set, but all sections will be on the same basis. Each section will have the option of taking the refund or not.
2. *One-half of initiation fee for new members:* Each local section will be refunded one-half, or $10.00 of the initiation fee of each new Member or Associate Member residing in its territory. How the disbursements will be made on initiation fees that are paid in installments has not yet been determined and this will likely influence the total amount refunded from initiation fees.
3. *No travel expense for section delegates in 1955* will be paid by the Institute. Expenses were paid for the current year, but starting next year each section must arrange the travel expense of its delegate to the Institute Annual Meeting.

Admittedly, the new plan will benefit some sections, and will work a hardship on others. The hardship cases will be handled individually. Most of the Petroleum sections will receive more money under the new plan than under the old, and the total for the Petroleum Branch will be more. Expenses for petroleum local sections in the Branch budget for 1953 totaled $4,663, whereas the total for 1954 is estimated at $6,500. A comparison of two specific sections is shown below, based on the assumption that these two sections will secure approximately the same number of new members in 1954 as they did in 1953. Junior members comprise 37 per cent of the Branch professional membership at the present time, so it was assumed that 63 per cent of the applications for 1953 were for the grades of Member and Associate to determine the number of applicants who will pay initiation fees. The figures are based on section membership for Jan. 1, 1954, which might not be used in calculating the refunds per member.

The figures below compare the status of a large section and a small one for the two years. In general, the larger sections will benefit more than the small ones, and sections that have a small membership with little potential for new members will be hard hit. However, most of the petroleum sections will fare rather well under the new plan, and most of them will have adequate funds to send a delegate to the 1955 Annual Meeting in Chicago if payment of his expenses is necessary.

The Petroleum Section Conference, composed of two representatives from each petroleum local section, voted in Dallas on Oct. 18, 1953, to recommend the discontinuance of all refunds to local sections after 1954, except for sections less than two years old. Although some of our sections reversed their position in the recent meeting in New York, it was on the premise that if refunds are granted they should be made on an equitable basis, and the petroleum sections agree generally with the philosophy that all local sections should be self supporting.

T. A. Pollard of Magnolia Field Research Laboratories in Dallas was appointed Petroleum Branch treasurer for 1954 by the Branch Executive Committee in its New York Meeting. As a part of his function as treasurer, he will undertake a study of the problems in financing of local sections, and this will undoubtedly result in some recommendations that may assist local sections with the problem.

As a matter of policy, the Petroleum Branch Executive Committee took the position in New York that it should not interfere with the financial affairs of local sections, except to render assistance where possible. However, the committee is unanimous in the belief that local sections should be financially self supporting, and the committee urges each section to aim toward reaching this goal as soon as possible. ★★★

	Membership Jan. 1, 1954	Approximate Number New Members and Associates Secured in 1953	1953 Institute Appropriation	Probable Revenue for 1954
Gulf Coast Section	829	50	$400	Refund: $415 In. Fee: $500 $915
Kansas Section	134	20	$100	Refund: $ 65 In. Fee $200 $265

D. W. AKINS . . . THOMAS C. FRICK

Petroleum Branch

Vice-Chairmen

1954

D. W. "Red" Akins knows the AIME "from the ground up," for he has served in just about every capacity in his rise to his newly-assumed job of vice-chairman of the Petroleum Branch.

After serving on local committees during the early days of his membership, he was chosen as a director of the East Texas Section in 1946 and 1947. Next, he was elected chairman of the Section in 1948. Then, in 1949, he was a section delegate to the Annual Institute Meeting, and in 1952 was instrumental in setting up the Lou-Ark Local Section, with headquarters in Shreveport, La.

Red is now division petroleum engineer in Shreveport for Ohio Oil Co., having followed a "from the ground up" rise, similar to his AIME progression, for 21 years. In 1933, the year following his graduation from Texas A&M, he joined the Ohio construction department in East Texas. After serving as a roustabout, pumper, and roughneck, he became an assistant petroleum engineer. Then his rise followed to petroleum engineer, district petroleum engineer for East Texas, and, finally, to his present position.

Fishing and duck-hunting in South Louisiana are Red's favorite sports. Caring for the lawn, trees, and flowers around the home he recently built in the North Highlands section of Shreveport is reportedly making deep inroads into his hunting and fishing time now. Three young Akins, sons aged 16 and 12, and a daughter aged 14, keep home life lively. Two additional fishing and hunting licenses are necessary each year since the boys are following their father's hobbies.

Akins is a member of the Shreveport Geological Society. He is very active in the API, having been a member of the Petroleum Practices Committee for several years. Currently he is a member of their Committee on Standardization of Wire Rope. — By R. W. TAYLOR

Thomas C. Frick, an Executive Committee member for three years and now chairman of the Branch Advertising Committee, is a new Branch vice-chairman for 1954.

The Corpus Christi, Tex., engineer has had an outstanding AIME and professional carrer. He joined the AIME in 1936 while he was teaching petroleum engineering at the University of Tulsa. Immediately he organized a student chapter at the Oklahoma school, introducing the AIME to many outstanding Petroleum Branch members of today.

He has served in many offices on the local section level. First, he was secretary-treasurer of the Mid-Continent Section, then chairman of the East Texas Section. Later he was chairman of the Permian Basin Section. Now he is a member of the Southwest Texas Section.

Since 1941, Tom has worked for Atlantic. Now he is a regional coordinator, and manager of land exploration and production activities. After receiving his BS in petroleum engineering from the University of Tulsa in 1933, Frick worked first with Phillips Petroleum Co. Then, in 1936, he returned to the University to teach petroleum engineering. While there he did some graduate study, before moving on to Atlantic.

Recently he was chosen for membership by the University of Tulsa chapter of the Pi Epsilon Tau Honorary Petroleum Engineering Fraternity.

The Fricks have two children — Martha, 18, a University of Tulsa student, and Charles, 15, a hunting and fishing companion of his father.

At present his primary interest in AIME work is in connection with his duties as head of the Advertising Committee of the JOURNAL OF PETROLEUM TECHNOLOGY. With other committee members, he is working to promote more and better advertising in the magazine. "I certainly feel honored to have been selected as vice-chairman of the Petroleum Branch," Frick states. "I have always enjoyed my work in the AIME and consider it *the* professional society to which all petroleum engineers should belong. — By R. W. TAYLOR

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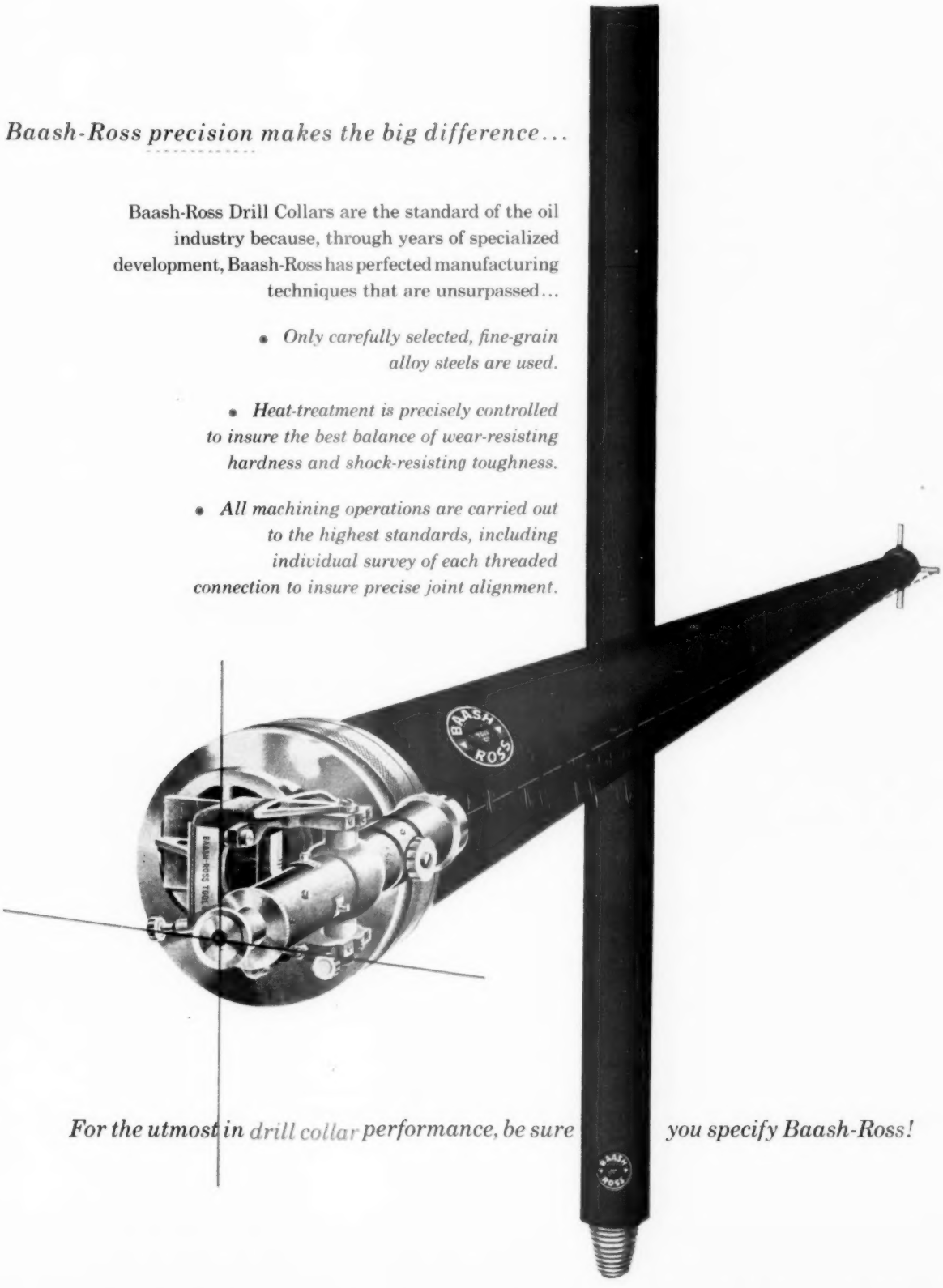

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AIME

PETROLEUM TRANSACTIONS

DISPLACEMENT EXPERIMENTS in a CONSOLIDATED POROUS SYSTEM

J. S. LEVINE
MEMBER AIME

SHELL DEVELOPMENT CO.
HOUSTON, TEXAS

T. P. 3759

ABSTRACT

A series of four displacement experiments has been run in a large alundum core. Flow potential distribution in each liquid phase was measured continuously through oil-wet and water-wet capillary barriers, using a null-point pressure balance, and saturated distribution was determined from electrical resistivity measurements. A method has been devised for calculating the effective (and relative) permeability to each phase at any time and at any point in the flow system for the transient displacement process. Relative permeability points have been calculated and average curves drawn for oil displacing water and water displacing oil. The values of dynamic capillary pressure have also been determined. Data have been substituted into the generalized Buckley-Leverett fractional flow equation and a comparison between actual and theoretical breakthrough recoveries is shown.

This paper is publication No. 38, Exploration & Production Research Division, Shell Development Co., Houston, Tex.

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office Aug. 3, 1953. Paper presented at the Petroleum Branch Fall Meeting in Dallas, Tex., Oct. 18-21, 1953.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1954, should be in the form of a new paper.

INTRODUCTION

Displacement experiments have been performed in the laboratory for many years in an effort to determine the effect of a number of parameters on multiphase flow in porous materials. In the literature of petroleum technology, Wyckoff and Botset[1] were among the first to develop the relative permeability concept and to show experimentally that oil, gas, and water can flow simultaneously through a porous medium in a precise way governed by certain fluid properties, by the relative saturation of each fluid, and by characteristics of the medium itself. Somewhat later, Leverett[2] and Hassler, Brunner, and Deahl[11] developed some theoretical concepts of capillary behavior in porous materials.

The work of Buckley and Leverett[3] presented a theoretical analysis of immiscible liquid displacement based on the equation of continuity and the Darcy equation for viscous flow of each fluid. Subsequent investigators attempting to verify the Buckley-Leverett equation have, in general, deliberately neglected the capillary pressure term or have performed experiments in such a manner that it could be neglected.

Terwilliger, *et al*[4] in 1951, obtained agreement between theory and experiment for the constant rate displacement of water by gas in a long vertical sand column. Rapoport and Leas[5] have investigated the

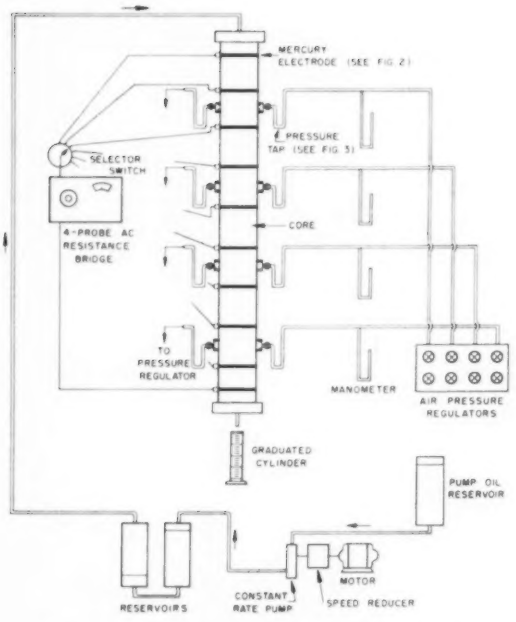


FIG. 1 — SCHEMATIC DIAGRAM OF APPARATUS.

properties of linear waterfloods in the laboratory and have shown that the recovery is related to a "scaling factor" containing the product of length of the system, velocity of the fluid, and viscosity of the fluid. The recovery becomes stabilized at certain values of the "scaling factor." They state that if the stabilized recovery is the same as that obtained by displacement through a capillary barrier, then the results of such experiments are applicable to the field.

Everett, Gooch, and Calhoun,[6] in studying the effect on recovery of liquid-liquid viscosity ratios and liquid-liquid miscibility, found the viscosity ratio to be the more significant parameter and concluded that viscous forces are more important than capillary forces with respect to recovery.

Welge[7] has shown a simplified method for computing recovery by gas or water drive based on the Buckley-Leverett equation. He postulates, however, that in the field the capillary pressure term may be neglected and, in the case of water flooding, the gravity term is normally negligible, too.

The effect of velocity on recovery has concerned several investigators. Earlougher[8] used radial flow through cores and found that as the fluid velocity increased the recovery increased. Rapoport and Leas[9] found the same effect for linear systems. However, Morse and Yuster,[9] and Holmgren[10] found that recovery was not materially affected by either pressure gradients or velocities in the systems which they studied.

Possibly no single parameter affecting the displacement mechanism has been studied more thoroughly than the relative permeability. Methods for measuring relative permeability have been developed by Hassler,[12,14] Morse, Terwilliger, and Yuster[12] and others. The measurement of relative permeability and factors affecting the measurement have received thorough investigation[15,16,17,18,19] in the past few years. The early work of Leverett and most of the other references cited have shown relative permeability to be independent of viscosity.

Odeh and Yuster[20] have recently presented data which indicate that the ratio of the oil permeability in a system containing water to the absolute permeability as measured with water may be greater than one and is a fraction of viscosity. Osoba, *et al*[15] and Geffen, *et al*[18] have shown that the relative permeability curves indicate a hysteresis and are, therefore, not unique functions of saturation but depend on the direction in which the saturation changes are made. Thus, the relative permeability is a function of the distribution of fluids in the system as well as of the amount of fluid.

The profusion of experimental work pertaining to fluid flow in porous media has revealed many details of the mechanism of multiphase flow. There did, however, appear to be a few gaps to justify further experimental work. In particular, no one has attempted to measure pressure distribution in each flowing phase during a displacement process in order to determine values of dynamic relative permeability and capillary pressure and to evaluate the effect of the interfacial forces. The work presented in this paper was undertaken in order to develop experimental techniques for measuring some of these parameters and to obtain a better understanding of the mechanism of displacement.

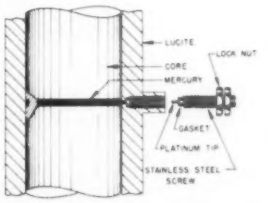
APPARATUS AND EQUIPMENT

All the experiments on which this paper is based were performed on a cylindrical alundum core having a total length of 53.9 cm and a cross-sectional area of 18.65 sq cm. The core had an average air permeability (extrapolated to infinite mean pressure) of 145 millidarcies and an average effective porosity of 25.1 per cent. A schematic diagram of the core and experimental set-up is shown in Fig. 1.

Ten small grooves, about 1/16-in. deep and 1/8-in. wide were machined around the circumference of the core at fixed points and were filled with powdered NaCl. A close-fitting lucite jacket was then bonded to the core at a pressure of 600 psi and a temperature of 200°C, after which holes were drilled into each salt groove. The salt was dissolved with water and these grooves then gave a continuous band around the core.

Before each experiment was started, the grooves were filled with mercury, which acted as electrodes, to give good surface contact with the pores of the core. The mercury was retained by means of platinum-tipped stainless steel screws which shouldered on thin gaskets and gave a good seal with the lucite. A detail of one of the mercury electrodes is shown in Fig. 2.

During an experiment, current was passed between the two electrodes near each end of the core. By means



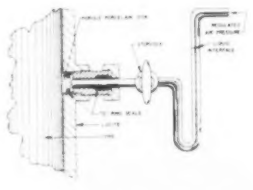


FIG. 2 (LEFT) — DETAIL OF MERCURY ELECTRODE.
FIG. 3 (RIGHT) — DETAIL OF PRESSURE TAP.

of a selector switch, the resistivity could be measured between any adjacent pair of electrodes with a 4-probe, 60-cycle a.c. resistance bridge. A resistivity-saturation curve was obtained on a separate piece of the core by measuring the resistance while the core was desaturated through a water-wet capillary membrane.[22] Resistance measurements made during any displacement experiment could then be converted to equivalent liquid saturations by means of the calibration curve. The saturation distribution throughout the column could be determined at any time.

The electrodes were spaced alternately at distances of 38 mm and 70 mm and the measured resistances obviously represented the average resistances over the respective intervals so that the saturations obtained were also average saturations. The saturation distribution was determined by drawing smooth curves through the points of average saturation plotted against the distance represented by the mid-point of the corresponding interval.

Fig. 3 shows the details of the pressure taps used to measure pressure in both oil and water at four equally spaced positions along the core. Pressure in the oil was measured through four porous porcelain disks which had been treated with G.E. "Dri-Film" in order to render them oleophilic. Pressure in the water was measured on the opposite side of the core through four porcelain disks which were normally hydrophilic. The disks were 1/2-in. in diameter and 1/10-in. thick. They were ground with plane faces so that they would make good contact with the core which was also milled plane at those places where the disks fit. A layer of Kleenex or diatomaceous earth was placed between the disk and core to offer better capillary contact with the wetting-phase liquid. The 0-ring seals insured that any oil or water flowing from the core and into the glass capillary tubing would flow through the oleophilic or hydrophilic disks respectively.

During an experiment, the liquid interfaces were continually maintained at the reference marks on the 1-mm diameter capillary tubes by means of regulated air pressure which could then be measured on external manometers. The air pressure necessary to keep the interface stationary is, therefore, equal to the pressure in the respective liquid at that position in the core. This method of measuring pressure was found to be very satisfactory. With experience, one could quickly adjust the pressure with volume changes of less than 0.2 cu mm. The 0-ring seals could easily be made leak-proof and any anomalies[23] in pressure measurement from this source are thought to be negligible.

All experiments were carried out in a thermostated cabinet at a temperature of 33°C ± 0.2°. The cabinet had plexiglas front panels through which control knobs were set to operate the pressure-tap stopcocks from the outside. A constant flow rate was maintained by means of Zenith Type "B" metering pumps. A special gearing arrangement and variable speed reducer allowed a wide range in pump output from 0.0005 to 0.20 cc/sec.

In order to reduce pump slippage to a minimum, only a high-viscosity oil (approximately 500 cp) was put through the pumps. This oil was then pumped into plexiglas reservoirs to displace the fluid to be flowed through the core. The reservoirs were in the cabinet to minimize volume changes due to temperature fluctuations.

DESCRIPTION OF FLUIDS USED

The water used in these experiments was an aqueous solution of 1-N NaCl to which had been added 1 per cent of formaldehyde to prevent bacteria formation; the term "water" in this paper always means a 1-N NaCl solution. A total of four runs will be reported. In three of the runs, the oil used was kerosene from which all the aromatics and unsaturates had been removed. In one run, the oil viscosity was increased by blending 25 per cent kerosene with 75 per cent mineral oil. Oil-water interfacial tension was about 39 dynes/cm determined by means of the pendent drop technique.

GENERAL PROCEDURE

Before each run, the core was thoroughly cleaned and dried and the air permeability measured in each interval over which resistance measurements were to be made by using the unfilled grooves as piezometer rings. The sectional permeabilities were found to vary about 20 per cent from the mean value.

The same general technique was followed in the four runs. First, the core was completely saturated under vacuum with the fluid to be displaced which was water in Runs 4, 5, and 7 and oil in Run 6. The porous disks which were to measure pressure in the displaced fluid were in place at the same time the core was saturated. The porous disks which were to measure pressure in the displacing fluid were saturated separately. They were put into place against the core after the core was saturated and before the displacement was started. The grooves were then filled with mercury. The core was mounted in the cabinet in a vertical position and the displacing fluid was forced into the top of the core and flowed vertically downward at a constant rate. The pressure tap stopcocks were opened and the liquid interfaces were continually kept at the reference marks (see Fig. 3). At frequent intervals (usually one-half hour), the manometer pressures, sectional resistivities, and volume of produced fluid were recorded. Readings were continued every half-hour to the time of breakthrough (24 to 48 hours) after which they were taken at less frequent intervals until no more of the displaced fluid was produced. Each displacement experiment lasted from 7 to 10 days.

EXPERIMENTAL RESULTS

Summary of Breakthrough and Final Recoveries

Table 1 summarizes some of the data of the four runs to be discussed in this report. Shown are the oil and water viscosities and densities, the total flow rates, and the saturation of displaced fluid at the time of breakthrough and at the end of production. It can be seen that for oil displacing water, a slightly higher breakthrough and total recovery are obtained for the higher flow rate (cf. Runs 4 and 5). At the same flow rate, the breakthrough and total recovery increases as the ratio of μ displacing/μ displaced increases (cf.

TABLE 1

Run No.	Displacing Liquid	Viscosity — cp* Oil	Viscosity — cp* Water	Density — gm/cc* Oil	Density — gm/cc* Water	Flow Rate cc/hour	Displaced Liquid Saturation Per Cent of Pore Volume at Breakthrough	Displaced Liquid Saturation Per Cent of Pore Volume at End of Production
4	Oil	1.64	0.854	0.814	1.036	6.31	44.0	34.8
5	Oil	1.66	.854	.814	1.036	3.72	48.0	36.8
6	Water	1.48	.854	.782	1.036	6.21	39.2	29.6
7	Oil	19.30	.854	.859	1.036	3.71	29.2	16.8

*At 33°C.

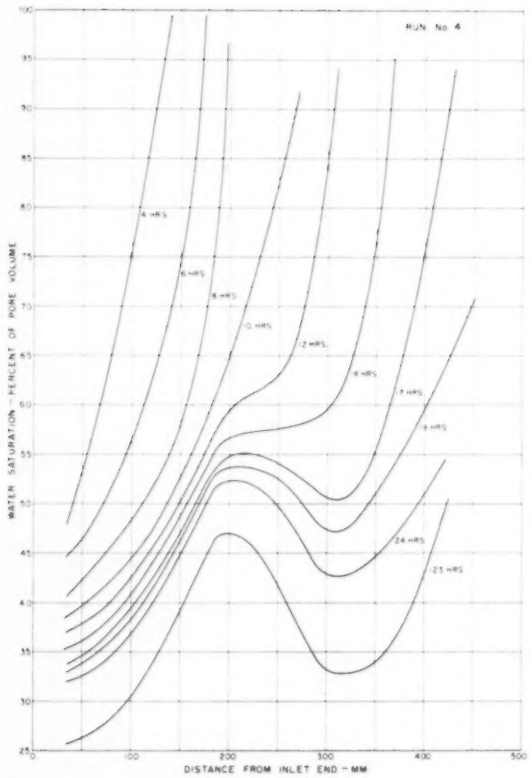


FIG. 4 — SATURATION DISTRIBUTION AT VARIOUS TIMES.

Runs 5 and 7). These results are in general agreement with the reported work of other investigators. In Run 6, where water displaced oil, the recoveries were higher than would have been anticipated from the low value of μ displacing / μ displaced.

SATURATION DISTRIBUTION AT VARIOUS TIMES

The values of water saturation were determined from the resistivity data and the saturations at various times were plotted as a function of distance from the inlet end of the core. A series of curves were obtained as shown in Fig. 4 where the saturation distributions are given for the displacement of water by oil in Run 4. The displacement is characterized by high saturation gradients for the first 10 hours with the distribution curve keeping the same general shape. After the flood front passes the approximate midpoint of the core and the water saturation reaches about 70 per cent there is an abrupt change in the gradient. This same general behavior was found in all four runs and is probably the result of a smaller average pore size (as indicated by a lower permeability) in the region between 170 to 300 mm.

FLOW-POTENTIAL DISTRIBUTION IN THE DISPLACING PHASE

In order to obtain the flow potential in each flowing phase, all pressure data were corrected to a datum plane corresponding to the bottom end of the core. The potentials were then plotted as a function of distance to give a series of curves as shown in Fig. 5 for the displacing (oil) phase of Run 4. It can be seen that the flow potential gradients in the displacing phase at a given distance decrease with time; the gradients are higher near the point of farthest penetration of the interface.

In Fig. 5, the potential lines are drawn only as far as pressure readings were obtained at the four pressure taps. Thus, at 10 hours, pressure readings were obtained at located at 79 mm and 192 mm, while those at 306 mm and 420 mm showed no pressure. At 12 hours, only the tap at 420 mm gave no reading. At 16 hours, pressure was obtained at all points of measurement. In Run 4, breakthrough occurred in about 22 hours, so that the 24-hour flow potential curve of Fig. 5 represents the distribution after breakthrough. It was found in all runs that the maximum flow potentials were reached in the displacing phase shortly after breakthrough and that they thereafter decreased to some lower equilibrium values. In every case, however, there was always a sharp potential drop near the end of the core.

FLOW-POTENTIAL DISTRIBUTION IN THE DISPLACED PHASE

Fig. 6 shows the flow-potential distribution in the displaced (water) phase at various times for Run 4. In this case, the gradients increase with time at a given distance. Since the displaced phase is continuous throughout the core — at least until such a low saturation is reached that the liquid film *may* be broken — pressure readings are obtained at all four taps for the duration of the experiment. Here the potential at the outflow face of the core must be zero and it can be seen that the curves approach zero in the vicinity of 539 mm.

The flow potentials in the displaced phase also decreased after breakthrough was reached. This is a condition necessary to the ultimate cessation of flow of the displaced phase, at which time the potential must be the same at all points. Actually this condition was never reached in any of the experiments. Even when the production of displaced fluid essentially ceased, there were still apparent slight saturation changes in the core (as indicated by resistivity measurements) which were sufficient to require a relatively high potential gradient.

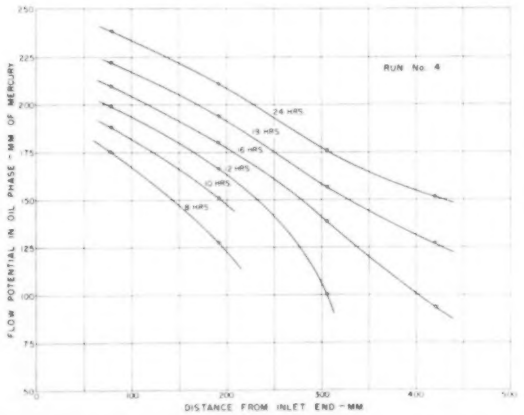


FIG. 5 — FLOW POTENTIAL DISTRIBUTION IN OIL PHASE AT VARIOUS TIMES.

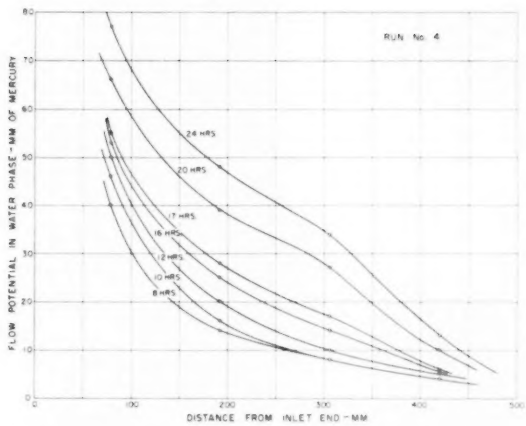


FIG. 6 — FLOW POTENTIAL DISTRIBUTION IN WATER PHASE AT VARIOUS TIMES.

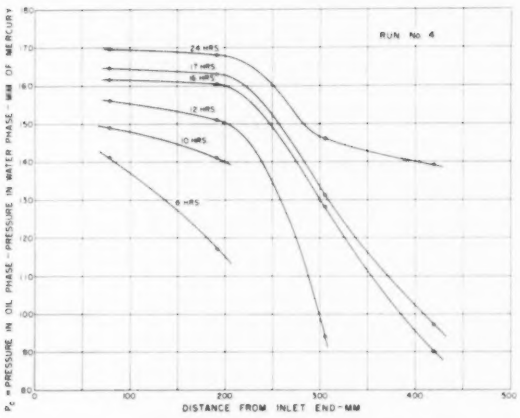

RUN No. 4
P_c = PRESSURE IN OIL PHASE - PRESSURE IN WATER PHASE - MM OF MERCURY
DISTANCE FROM INLET END - MM
24 HRS
17 HRS
15 HRS
12 HRS
10 HRS
8 HRS

FIG. 7 — VARIATION OF CAPILLARY PRESSURE DISTRIBUTION WITH TIME.

The greatest experimental difficulty in this work was encountered in determining the pressure in the displaced phase because of the problem of maintaining capillary contact at low liquid saturation. The present technique for measuring pressure — while essentially a zero volume displacement method — does require a small fluid movement across the barrier. When the saturation of displaced fluid in the core is low, even a slight fluid movement from the core must take place through relatively fine liquid filaments so that the position of the interface in the capillary manometers changes very slowly for any pressure unbalance. In those few instances where capillary contact was apparently lost between the porous disk and the core, it was found impractical to reestablish contact by forcing small volumes of fluid back into the core at that point.

DYNAMIC CAPILLARY PRESSURE MEASUREMENTS

In the same sense that all the pressure measurements essentially represent instantaneous values for a transient process, then the difference in pressure between displacing and displaced phase at any of the four points of measurement can be considered to represent a dynamic capillary pressure. Fig. 7 shows this capillary pressure as a function of distance at various times. After breakthrough, the capillary pressure distribution is characterized by two regions having a low gradient separated by a region having a high gradient. This latter region corresponds to the one showing the negative saturation gradients in Fig. 4. With the distance along the core always measured as positive downward and the capillary pressure always the difference in pressure between displacing and displaced phase, then the capillary pressure gradient was always found to be a negative value regardless of whether oil or water was the displacing medium.

Fig. 8 shows the dynamic capillary pressure plotted as a function of displaced phase saturation. The values can be obtained by combining Figs. 4 and 7. If the core were completely homogeneous and capillary pressure were uniquely a function of saturation, then the data should define a single curve in Fig. 8. As can be seen, three separate capillary pressure curves are actually obtained. This behavior repeated itself in all runs and is apparently the result of inhomogeneity of the core.

CALCULATION OF DYNAMIC RELATIVE PERMEABILITY

Figs. 4 to 8 have shown a portion of the data obtained during one experiment in which oil displaced water. A large amount of similar data was also obtained for three other runs which were varied as indicated in Table 1. One of the objectives of this investigation was to arrive at a method for calculating the dynamic relative permeability values for each phase during a transient displacement process.

The calculation of dynamic permeability at a particular time and at a given point in the system can be accomplished if one knows the instantaneous flow rate and flow potential gradient. According to the well-known Darcy equations:

$$k_o(t, Z) = -\frac{\mu_o q_o}{A\dfrac{\partial \phi_o}{\partial Z}} \quad \ldots\ldots\ldots \quad (1)$$

$$k_w(t, Z) = -\frac{\mu_w q_w}{A\dfrac{\partial \phi_w}{\partial Z}} \quad \ldots\ldots\ldots \quad (2)$$

where k_o and k_w = effective permeability to oil and water respectively in darcies
μ = viscosity in centipoises
A = cross-sectional area in cm²
q = flow rate in cm³/second
t = time in seconds
ϕ = flow potential in atmospheres
Z = distance in direction of flow in cm
subscripts $_o$ and $_w$ refer to oil and water respectively.

For the displacement of water by oil then, from the curves of Figs. 5 and 6, the values of $\partial\phi_o/\partial Z$ and $\partial\phi_w/\partial Z$ at a particular time and distance can be determined by graphical differentiation. The value of q_o at the same time and distance can be obtained from the equation:

$$q_o = q_{io} - c\int_0^Z \left(\frac{\partial S_w}{\partial t}\right) dZ \quad \ldots\ldots\ldots \quad (3)$$

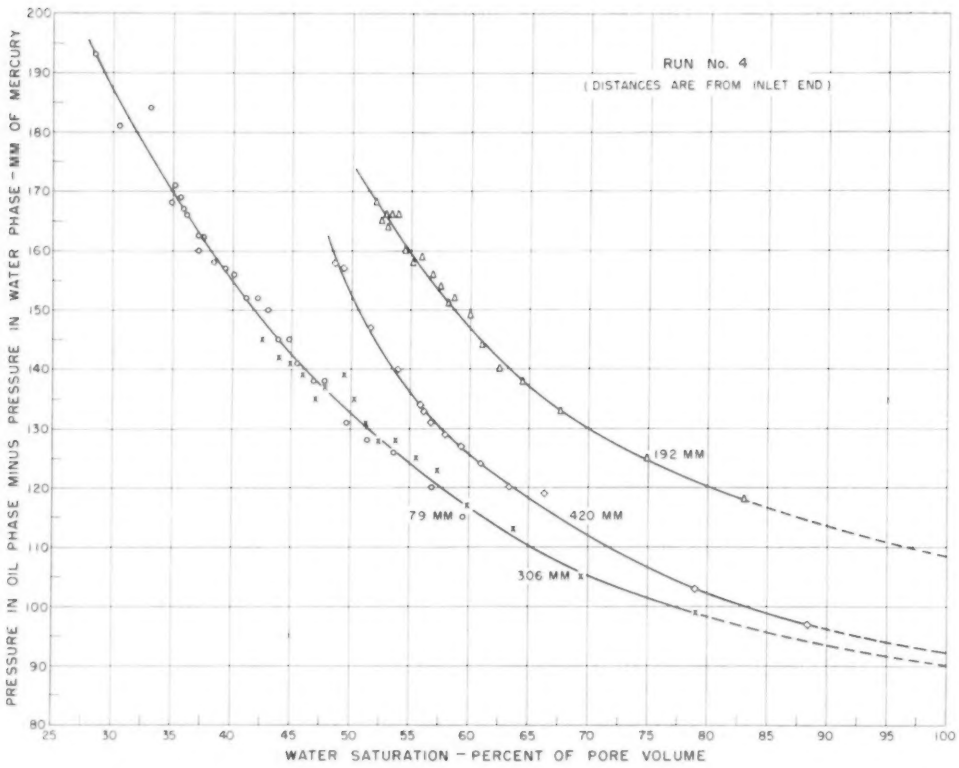

RUN No. 4
(DISTANCES ARE FROM INLET END)
192 MM
420 MM
306 MM
79 MM
PRESSURE IN OIL PHASE MINUS PRESSURE IN WATER PHASE - MM OF MERCURY
WATER SATURATION - PERCENT OF PORE VOLUME

FIG. 8 — VARIATION OF CAPILLARY PRESSURE WITH SATURATION AT FOUR POSITIONS ALONG THE CORE.

where q_{1o} = constant flow rate of oil into input end of core
S_o = fractional oil saturation in core
c = constant (cross-sectional area × fractional porosity)

From Fig. 4, a series of curves of oil saturation as a function of time for various fixed distances can be obtained. From the derivative of each curve at different times, another series of curves of $\partial S_o/\partial t$ as a function of distance can be plotted. The integral term in Equation (3) can then be evaluated by integrating the area under each curve to the desired distance. Thus, sufficient data are available to substitute into Equation (1) to calculate the oil permeability at a given saturation. Inasmuch as the oil and water can be considered incompressible, and the pore volume is completely filled with liquid, the rate at which oil accumulates in any part of the core is equal to the rate at which water is removed from the same part. Thus, the instantaneous water flow rate at any time and distance is numerically equal to the value of the constant times the integral term in Equation (3), and $k_w(t, Z)$ can be calculated from Equation (2). If the k_o and k_w values are divided by the absolute permeability of the core, two points of relative permeability as a function of saturation are then obtained. The entire procedure can then be repeated at any other time and distance.

Fig. 9 shows the points obtained using the above procedure on the data of Runs 4, 5, and 7, in all of which water was displaced by oil. It is apparent at once that there is considerable spread of the calculated points about some average value as indicated by the curves. If sufficient points are calculated, it seems reasonable to assume that average curves representing the true dynamic relative permeability can be obtained.

It is significant to note that in Fig. 9 the values for relative permeability to oil for Run 7 are approximately the same as for Runs 4 and 5 even though the oil/water viscosity ratio was almost 12 times as great. This indicates that in this range, at least, the relative permeability is independent of viscosity.

The procedure outlined above was also repeated with the data of Run 6 in which water displaced oil from the core. The points fell closer to an average curve than did those of Fig. 9. In Fig. 10 are shown the average curves for the displacement of water by oil in Runs 4, 5, and 7, and the average curves for the displacement of oil by water in Run 6. They are plotted as a function of water saturation. A comparison of the curves will show the apparent effects of wettability on the flow characteristics. If the assumption is made that the porous material has an equal affinity for both oil and water, then the dotted oil curve should be a mirror image of the solid water curve and the solid oil curves should be a mirror image of the dotted water curve about the 50 per cent saturation line.

In other words, if all relative permeability values were plotted as a function of *displaced* phase saturation, only two curves should result if the assumption of equal affinity were correct. This is obviously not the case. The relative water permeability for a system in which water displaces oil is less than the relative oil permeability for a system in which oil displaces water for *the same saturation of displaced fluid*. From this, one may infer that in the porous solid used in these studies the solid

surface showed a greater affinity for water, so that, in general, water flowed in smaller pores than did oil at any given saturation. If, on the other hand, wettability is assumed to be indicated by the sign of the capillary pressure term, then the *displacing* fluid is always the *apparent* nonwetting fluid since the pressure in the displacing phase was always found to be greater than in the displaced phase.

Another fact that becomes apparent from Fig. 10 is that the displacing phase relative permeability goes to zero *only at zero saturation of displacing phase* in these dynamic displacement processes. In this respect, the relative permeability curves obtained by the method described differ from the usual equilibrium relative permeability curves in which the displacing fluid relative permeability becomes zero at saturations of that fluid greater than zero. Thus, the dotted oil curve and the solid water curve of Fig. 10 would more closely approximate values obtained by an equilibrium process. It becomes apparent then that to make reservoir calculations based on relative permeability data for, say, a water flooding process, relative permeability curves obtained by dynamic displacement of oil by water should be used.

CALCULATION OF THE BREAKTHROUGH RECOVERY

In order to calculate the breakthrough recovery, the theory and technique developed by Buckley and Leverett[1] have been applied. By using the generalized Darcy equations for each fluid, Equations (1) and (2), they have developed an equation which relates the fraction of one fluid in the flow stream to the viscous and capillary forces existing in the system. In our notation, this equation is:

$$F_1(S_1) = \frac{1 - \frac{k_2 A}{Q_t \mu}\left[\frac{g\Delta\rho}{b} + \frac{\partial P_c}{\partial Z}\right]}{1 + \frac{k_2 \mu_1}{k_1 \mu_2}} \quad . \quad . \quad . \quad (4)$$

where F_1 = fraction of displacing fluid in flow stream
S_1 = saturation of displacing fluid
k_e = effective permeability in darcies
Q_t = total flow rate in cm³/second
P_c = pressure in displacing phase minus pressure in displaced phase in atmosphere
g = acceleration of gravity in cm/second²
$\Delta\rho$ = density of displaced phase minus density of displacing phase in gm/cm³
Z = distance in direction of flow in cm
b = 1.013 (10^6) dynes/cm²/atmosphere
subscripts 1 and 2 always refer to displacing and displaced phase respectively.

A method has already been indicated for calculating relative permeability as a function of saturation. Inasmuch as

$$k_1 = k_{r1} k \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and

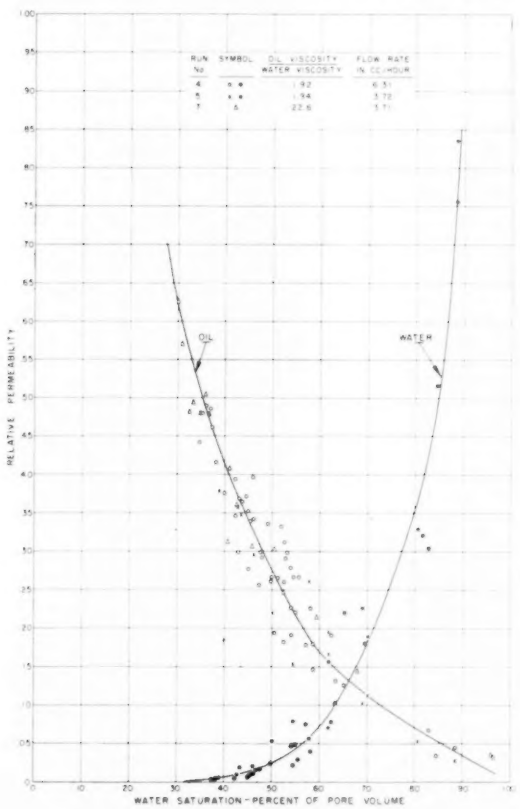


FIG. 9 — DYNAMIC RELATIVE PERMEABILITY CHARACTERISTICS FOR THE DISPLACEMENT OF WATER BY OIL.

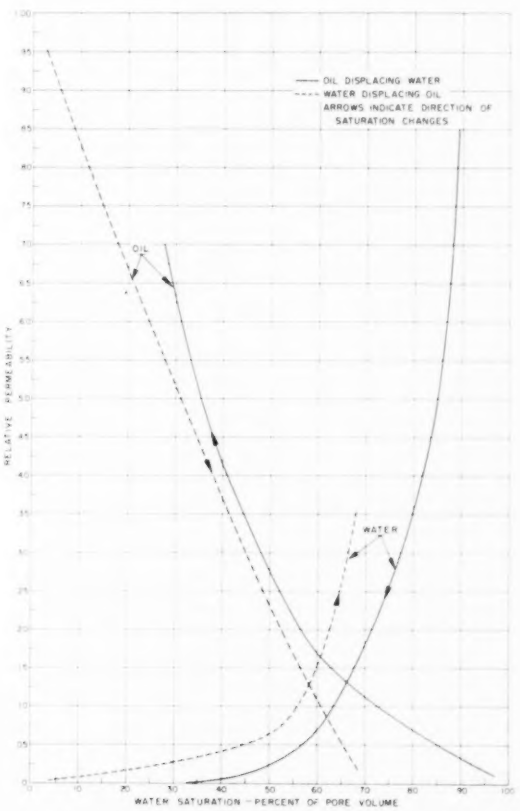


FIG. 10 — COMPARISON OF DYNAMIC RELATIVE PERMEABILITY CHARACTERISTICS FOR TWO TYPES OF DISPLACEMENT.

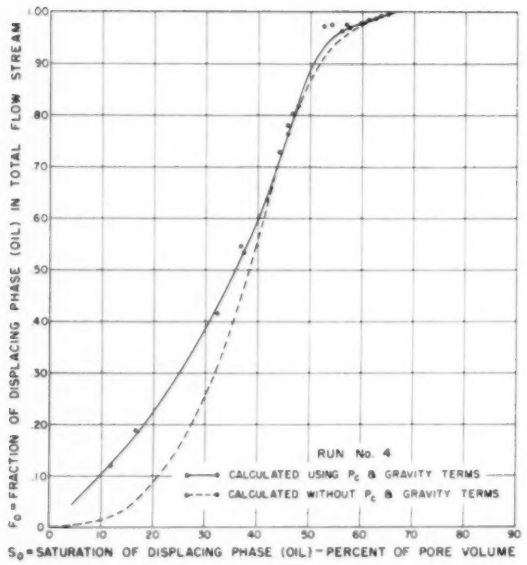

RUN No. 4
CALCULATED USING P_c & GRAVITY TERMS
CALCULATED WITHOUT P_c & GRAVITY TERMS
F_o = FRACTION OF DISPLACING PHASE (OIL) IN TOTAL FLOW STREAM
S_o = SATURATION OF DISPLACING PHASE (OIL) – PERCENT OF PORE VOLUME

FIG. 11 — COMPARISON OF F_o CURVES DETERMINED WITH AND WITHOUT CAPILLARITY AND GRAVITY TERMS FOR THE DISPLACEMENT OF WATER BY OIL.

$$k_e = k_r k \quad \ldots \quad (6)$$

where k_r = relative permeability
k = absolute permeability in darcies,

the effective permeability can be obtained for each fluid at any saturation. All that remains for a determination of $F_1(S_1)$ from Equation (4) is an evaluation of the capillary pressure gradient $\partial P_c/\partial Z$. This can be determined from Fig. 7 by graphical differentiation at the desired distance and time. Thus, the fraction of displacing fluid in the flow stream can be calculated at all points of distance and time. This fraction has been

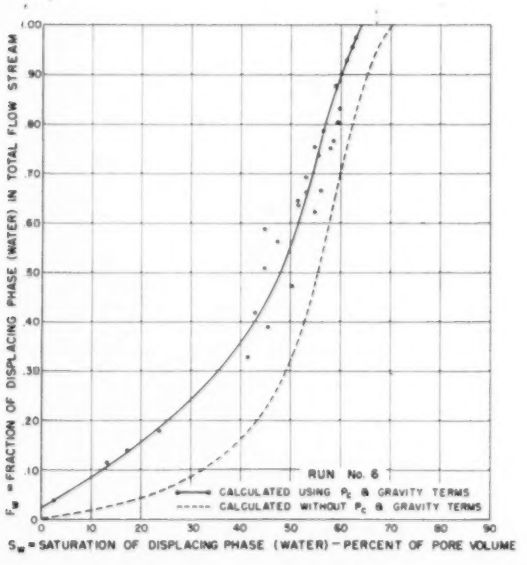

RUN No. 6
CALCULATED USING P_c & GRAVITY TERMS
CALCULATED WITHOUT P_c & GRAVITY TERMS
F_w = FRACTION OF DISPLACING PHASE (WATER) IN TOTAL FLOW STREAM
S_w = SATURATION OF DISPLACING PHASE (WATER) – PERCENT OF PORE VOLUME

FIG. 12 — COMPARISON OF F_w CURVES DETERMINED WITH AND WITHOUT CAPILLARITY AND GRAVITY TERMS FOR THE DISPLACEMENT OF OIL BY WATER.

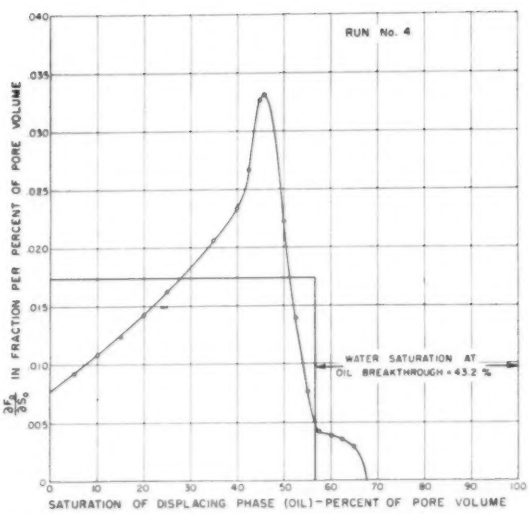

RUN No. 4
WATER SATURATION AT OIL BREAKTHROUGH = 43.2 %
$\frac{\partial F_o}{\partial S_o}$ IN FRACTION PER PERCENT OF PORE VOLUME
SATURATION OF DISPLACING PHASE (OIL) – PERCENT OF PORE VOLUME

FIG. 13 — CONSTRUCTION FOR CALCULATING BREAKTHROUGH RECOVERY FROM F_o CURVE.

calculated from the experimental data for the displacement of water by oil (Run 4) and the displacement of oil by water (Run 6) and is shown in Figs. 11 and 12, respectively, as a function of displacing phase saturation.

Also shown in each figure is the fraction calculated from Equation (4) with the capillary pressure and gravity term assumed equal to zero. It can be seen that the net effect of including the bracketed term is always to increase the F_1 value at any saturation. This means that the capillary pressure gradient always acts to decrease the recovery of displaced fluid. The effect is less pronounced in Run 4 than in Run 6.

Breakthrough recovery can be calculated from the theory by making use of what might be called the Buckley-Leverett construction (which has been explained in detail by Pirson).[22] Fig. 13 shows the $\partial F_o/\partial S_o$ versus S_o curve for Run 4. The horizontal line is drawn so that the area under it up to the intersection with the curve on the right is equal to the area under the curve up to that point. The vertical line is then drawn so that the area in the rectangle is equal to the total area under the curve. The average residual saturation of displaced fluid at the time of breakthrough is then equal to the difference between 100 and the displacing phase saturation indicated by the vertical line. For Run 4, the residual saturation at breakthrough is calculated to be 43.2 per cent. This compares with 44.0 per cent determined experimentally.

Fig. 14 shows the same construction for Run 6. In this case the oil saturation at water breakthrough was calculated to be 36.0 per cent which compares with an experimental value of 39.2 per cent. If the F_w curve which neglected capillary pressure and gravity had been used, the discrepancy would have been about six pore volume per cent greater. Table 2 shows a comparison

TABLE 2 — COMPARISON OF EXPERIMENTAL AND CALCULATED DISPLACED LIQUID SATURATION AT BREAKTHROUGH.

Run No.	Displaced Liquid Saturation at Breakthrough — Per Cent of Pore Volume	
	Experimental	Calculated from Data Using Eq. 4
4	44.0	43.2
5	48.0	44.5
6	39.2	36.0
7	29.2	32.5

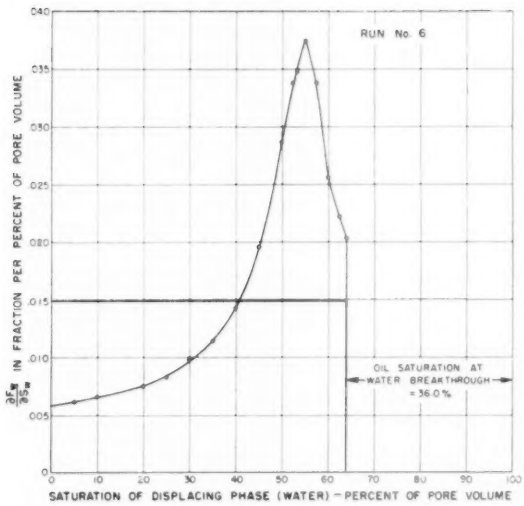


FIG. 14 — CONSTRUCTION FOR CALCULATING BREAKTHROUGH RECOVERY FROM F_w CURVE.

between the experimental and calculated displaced liquid saturations at breakthrough.

In the preceding calculation of F_1 for Runs 4 and 6, the value of $-[k_2A/Q_1\mu_2][(\partial P_c/\partial Z) + (g\Delta\rho/b)]$ was determined at various saturations for different positions of distance and time. Fig. 15 shows a plot of this term versus the displacing fluid saturation. It can be seen that the value for the entire term approaches a maximum at zero saturation and approaches zero at about 70 per cent saturation of displacing liquid. The function, however, is different depending on the type of displacement.

Fig. 16 shows the values of $\partial P_c/\partial Z$ at various saturations which were calculated from the curves of Fig. 15. It should be remembered that P_c is defined as the difference in pressure between displacing and displaced phases so that in Run 4, $P_c = P_o - P_w$, and in Run 6, $P_c = P_w - P_o$. It is readily apparent that even at the same flow rate, the capillary pressure gradient versus saturation curve for the displacement of water by oil is not the same as for the displacement of oil by water. Furthermore, where the flow rates differ for the same type of displacement, i.e., water by oil, it can be seen that $\partial P_c/\partial Z$ is a function of rate. The gradient curves converge at high displacing phase saturation so that the gradient is more sensitive near the flood front to a change in rate than in the region which has been more completely flooded.

The manner in which $\partial P_c/\partial Z$ varies as a function of Q_t will determine whether, in the laboratory at least, the recovery of displaced fluid will change as the total flow rate changes. Specifically, if the value of $([\partial P_c/\partial Z) + g\Delta\rho]$ is directly proportional to Q_t, then the breakthrough recovery should be independent of rate. Thus it becomes necessary to know how the capillary pressure gradient varies with flow rate in order to predict whether changing the rate will change the recovery.

SUMMARY AND CONCLUSIONS

1. A series of four linear displacement experiments have been performed on an alundum core. Techniques were employed which allowed continuous measurements at various positions along the core of the saturation

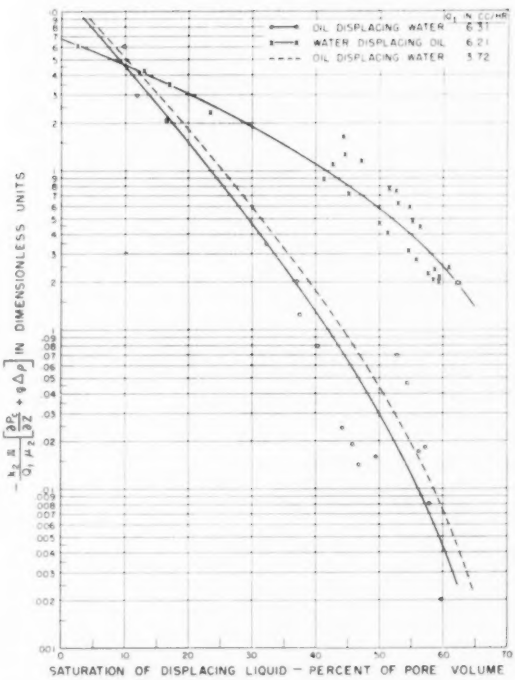

OIL DISPLACING WATER 6.31
WATER DISPLACING OIL 6.21
OIL DISPLACING WATER 3.72
SATURATION OF DISPLACING LIQUID – PERCENT OF PORE VOLUME

FIG. 15 — VARIATION OF THE CAPILLARITY AND GRAVITY TERMS WITH FLOW RATE AND TYPE OF DISPLACEMENT.

distribution and pressure distribution in each flowing phase.

2. A method was developed for calculating the dynamic relative permeability as a function of saturation. The resulting curves for the displacement of

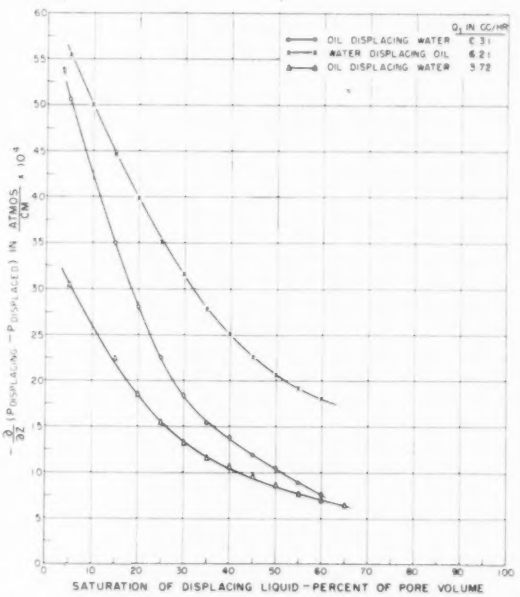

OIL DISPLACING WATER 6.31
WATER DISPLACING OIL 6.21
OIL DISPLACING WATER 3.72
SATURATION OF DISPLACING LIQUID – PERCENT OF PORE VOLUME

FIG. 16 — VARIATION OF THE CAPILLARY PRESSURE GRADIENT WITH FLOW RATE AND TYPE OF DISPLACEMENT.

water by oil and oil by water showed that relative permeability was not a unique function of saturation but depended on the direction of saturation change. It was shown that relative permeability was also not a unique function of *displaced* phase saturation. This is possibly the result of a difference in wettability of the porous system.

3. The displacing phase relative permeability goes to zero only at zero saturation of that phase in these dynamic displacement processes.

4. In the range studied, relative permeability appeared to be independent of viscosity.

5. The Buckley-Leverett fractional flow equation gives reasonable agreement between calculated and experimental breakthrough recoveries if the capillary pressure and gravity terms are retained. If capillary pressure is defined as the difference in pressure between displacing and displaced phases, then the experimental values of $\partial P_c/\partial Z$ were always negative. Thus, the net effect of including the capillarity term is to increase the value of the calculated fraction of displacing fluid in the flow stream at any saturation and to decrease the recovery of displaced fluid.

6. The capillary pressure gradient was calculated as a function of displacing phase saturation for the two types of displacement, and two different gradient curves were obtained for the same total flow rate. When the same type of displacement was involved, i.e., the displacement of oil by water, $\partial P_c/\partial Z$ was found to be a function of total flow rate.

ACKNOWLEDGMENT

The author wishes to thank M. O. Thaemar and R. D. Ward for performing a large part of the experimental work and for making many of the calculations reported in this paper. He also wishes to express his appreciation to C. H. Fay, W. R. Purcell, and C. S. Matthews of Shell Development Co. for their helpful comments, suggestions, and criticisms.

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EQUILIBRIUM VAPORIZATION RATIOS for a RESERVOIR FLUID CONTAINING A HIGH CONCENTRATION of HYDROGEN SULFIDE

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ABSTRACT

Equilibrium vaporization ratios were obtained for light hydrocarbons, nitrogen, carbon dioxide, and hydrogen sulfide in a reservoir fluid containing 35 mole per cent hydrogen sulfide. The data cover the range from 700 to 2500 psia at 154°F.

The results of this study are compared with results obtained by other investigators on systems containing less hydrogen sulfide. When large amounts of hydrogen sulfide are present, the equilibrium vaporization ratios for ethane and heavier hydrocarbons are greater than the ratios for systems containing little or no hydrogen sulfide. Large amounts of hydrogen sulfide have the reverse effect on the ratios for methane.

Routine PVT studies were performed on the reservoir fluid including flash and differential liberations of the dissolved gas. The pressure-volume relationships of the saturated fluid were also determined.

It is shown that the use of published correlations on physical properties of reservoir fluids can lead to gross errors when applied to systems containing large amounts of hydrogen sulfide.

INTRODUCTION

Equilibrium vaporization ratios for various components in naturally occurring crude oil and condensate systems have been reported in the literature.[1,2,3,4] Recently, several papers have been published with emphasis on non-hydrocarbon components such as nitrogen, carbon dioxide and hydrogen sulfide.[5,6,7,8,9] The increased discovery of reservoir fluids having high concentrations of these non-hydrocarbon components, particularly hydrogen sulfide, has created a need for a further study of their phase behavior.

Equilibrium vaporization ratios are known to vary with pressure, temperature, and overall composition of the system.[10] It was anticipated that ratios for systems containing large amounts of hydrogen sulfide would differ from the ratios for systems containing small amounts of hydrogen sulfide. Therefore, the present work was undertaken in order to obtain reliable equilibrium vaporization ratios for the reservoir-fluid in question.

PROCEDURE

The procedure followed was evolved after considerable experimentation on methods of handling the very sour crude. It was found that drying agents (e.g. $CaCl_2$ and $CaSO_4$) absorbed an appreciable amount of hydrogen sulfide from the gas used to prepare the recombined samples. The concentration of hydrogen sulfide dropped as much as 10 mole per cent in a single pass through a 3-ft drying tube.

It was also found that when undried gas was agitated with mercury in the PVT cell, a black scum, believed to be mercuric sulfide, was formed and the hydrogen sulfide content of the gas dropped several mole per cent. Because composition changes during a run could not be tolerated, separation of the mercury and sour fluid was necessary. In order to effect this separation, a stainless steel piston, equipped with Teflon O-rings, was placed in the PVT cell between the mercury and the sour fluid. This piston had to be constructed in three parts because

[1]References given at end of paper.

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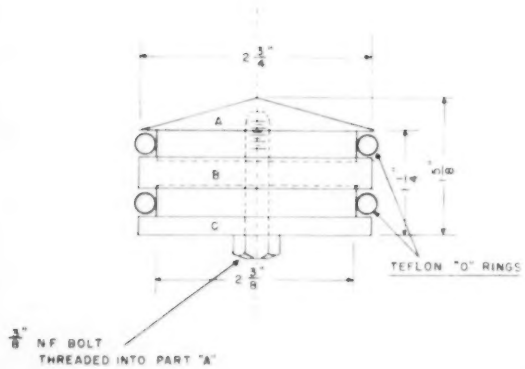

FIG. 1 — STAINLESS STEEL PISTON FOR USE WITH SOUR CRUDES IN RUSKA PVT CELL (ASSEMBLED).

the Teflon 0-rings would not stretch enough to pass over the piston to seat in the 0-ring grooves. The top of the piston was designed to conform with the top of the PVT cell, so that the liquids in the cell could be completely displaced. Fig. 1 shows the assembled piston.

The reservoir fluid used in this study was made by recombination of high pressure separator gas and liquid samples. These samples were recombined in the PVT cell according to the producing gas-oil ratio and were then agitated to equilibrium at the reservoir pressure of 2500 psia and reservoir temperature of 154°F.

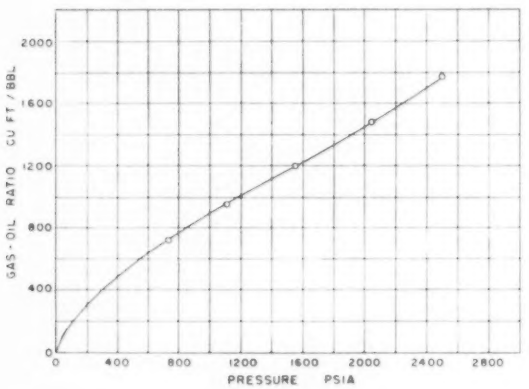

FIG. 2 — SOLUTION GAS-OIL RATIO VERSUS PRESSURE, BASED ON RESIDUAL OIL AT 60°F AND 14.7 PSIA.

TABLE 1 — GAS-OIL RATIOS AND VOLUME FACTORS OF RESERVOIR FLUID

Pressure psia	Gas-Oil Ratio in Solution Std. cu ft/bbl residual oil	Volume Factor $\left(\frac{V_s}{V_r}\right)^*$
2745	—	1.884
2600	—	1.889
2545	—	1.891
2500	1772.0	1.894
2043	1478.3	1.762
1554	1197.0	1.637
1111	949.0	1.530
726	730.3	1.447

Gravity of Residual Oil — 34.0 API

*V_s = volume of saturated oil at the saturation pressure.
V_r = volume of residual oil at 60°F and 14.7 psia.

Any excess gas was displaced, leaving a sample with a bubble point of 2500 psia and 154°F.

Routine PVT data were obtained on this sample, including flash and differential gas liberations. The differential liberation consisted of a series of flash liberations at progressively lower pressures. Because of the large volume of gas required to make an accurate LTD analysis, it was necessary to take pressure decrements of approximately 500 psia. For this reason, it was possible to make only five successive flash liberations on the sample; of course, use of smaller pressure decrements would have approximated the true differential liberation more closely.

The procedure followed in performing the differential gas liberation was as follows: the pressure on a sample of saturated reservoir fluid, at reservoir temperature, was lowered below the bubble point pressure by withdrawing mercury from the bottom of the PVT cell. A gas phase was formed which was brought to equilibrium with the liquid phase by prolonged agitation. After equilibrium was attained, the gas phase was displaced from the cell at constant pressure; the pressure was maintained by injecting a volume of mercury equal to the volume of the gas displaced. When the cell was again liquid full, additional mercury was withdrawn; thus, a new gas phase was formed which was then agitated until it was at equilibrium with the coexisting liquid phase. This gas was then displaced at constant pressure.

This sequence was repeated until the cell contained a saturated liquid with a bubble point pressure of approximately 700 psia. The volume of the PVT cell, containing the stainless steel piston, was not large enough to allow expansion of the system to atmospheric pressure. Therefore, mercury was withdrawn from the bottom of the cell at this point, to form a gas phase

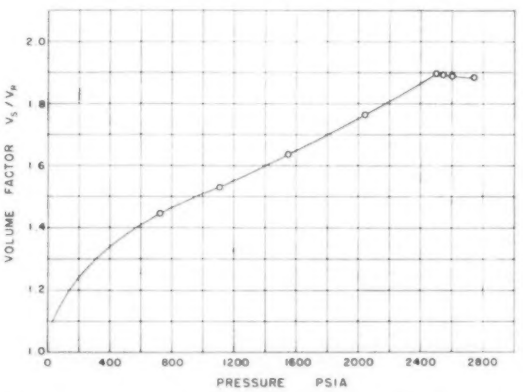

FIG. 3 — VOLUME FACTOR VERSUS PRESSURE, BASED ON RESIDUAL OIL AT 60°F AND 14.7 PSIA.

TABLE 2 — FLASH LIBERATION OF SATURATED RESERVOIR FLUID

Saturation pressure of fluid (psia)	2500
Separator gauge pressure	0
Solution gas-oil ratio, $\frac{\text{cu ft}}{\text{bbl residual oil}}$	1938
Stock tank API gravity at 60°F	32.6
Molecular wt, stock tank oil	201
Shrinkage factor, V_t/V_s*	0.5168
Formation volume factor, V_s/V_t	1.935
Specific gravity of flashed gas	1.031

*V_s = volume of saturated oil at the saturation pressure.
V_t = volume of stock tank oil at 60°F and 14.7 psia.

in the cell, and gas was released through the valve at the top of the cell until atmospheric pressure was reached. The residual oil was analyzed and its volume was determined.

From the volume of gas bled off at each pressure and the volume of residual oil, corrected to 60°F, the gas-oil ratios and volume factors were determined. The gas sample bled off at each liberation pressure was subjected to LTD analysis. The volume of each sample was determined by passing the gas into a 5-gal. carboy filled with saturated brine. A volume of brine equal to the gas volume entering the carboy was displaced and weighed.

Equilibrium vaporization ratios were calculated by mathematical recombination in the following manner: the volume and composition of the gas liberated at each pressure during the differential liberation were used to determine the number of moles of each component in each liberated gas volume. The composition, weight and molecular weight of the residual liquid remaining at the end of the gas liberation were also determined. From these data the number of moles of each component in the gas liberated in the pressure drop from 726 psia to atmospheric (the final pressure drop in the gas liberation process) was then added to the number of moles of the corresponding component in the liquid phase (residual oil). The summation gave the composition of the saturated liquid at 726 psia.

The composition of the equilibrium gas liberated at 726 psia was known, so a set of equilibrium vaporization ratios (at 726 psia) was calculated. The number of moles of each component in the gas liberated between 1111 and 726 psia was then added to the number of moles of that component in the saturated liquid at 726 psia. This gave the composition of the saturated liquid at 1111 psia. The composition of the equilibrium gas liberated at this pressure was known also, so a set of equilibrium vaporization ratios was calculated for 1111 psia. This process was followed until all of the gas was recombined with the residual oil.

DISCUSSION OF RESULTS

The results of the PVT study of the fluid under consideration are presented in Tables 1, 2, and 3 and Figs. 2, 3, and 4.

Table 1 and Fig. 2 present the gas-oil ratio data obtained for a differential liberation at 154°F. The gas solubility curve is similar to the curves usually obtained for ordinary crude oil systems. Only five points are presented because of the large pressure drops required to provide enough gas for accurate LTD analysis. The volume factors obtained from the differential liberation are presented in Fig. 3.

Table 2 presents the results of a flash liberation of the reservoir fluid to atmospheric pressure. No abnormal behavior was noted in this case.

Attempts were made to apply the bubble point — gas-oil ratio correlations of Standing[11] and Katz[12] to the present experimental data. Values of bubble point derived from these correlations were found to be over 100 per cent in error. Perhaps this is to be expected, since the correlations were not developed for this type of system.

The pressure-volume relations for the system are presented in Fig. 4 and Table 3.

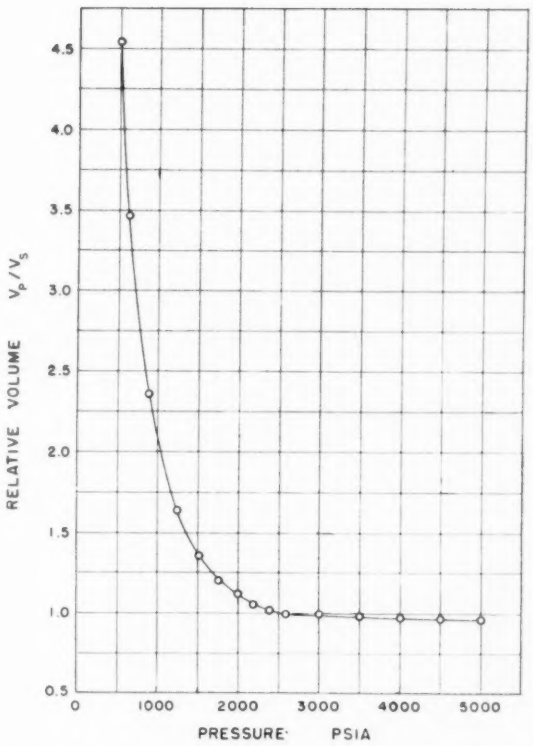

FIG. 4 — RELATIVE VOLUME OF RESERVOIR FLUID VERSUS PRESSURE AT 154°F.

TABLE 3 — PRESSURE-VOLUME RELATIONS FOR RESERVOIR FLUID AT 154°F

Pressure PSIA	Relative Volume $\frac{V_p^*}{V_s}$
5000	0.9594
4500	0.9667
4000	0.9750
3500	0.9826
3000	0.9915
2592	0.9998
2500	1.0000
2388	1.020
2180	1.063
1970	1.124
1750	1.215
1520	1.360
1245	1.635
890	2.368
648	3.470
518	4.548

*V_p = Combined volume of oil and gas at given pressure.
V_s = Volume of saturated fluid at saturation pressure.

The results of the LTD analysis of the gas samples taken during the gas liberation are given in Table 4 and Figs. 5a and 5b. The last two columns in Table 4 represent the composition of the total gas evolved in dropping the pressure from the given pressure down to atmospheric. Therefore, this gas was not in equilibrium with the residual oil at atmospheric pressure and K values could not be calculated for atmospheric pressure.

It will be noted that more points are presented on the methane, ethane, carbon dioxide, propane, and hydrogen sulfide curves than appear on those for the butanes and heavier components. Two separate pressure-

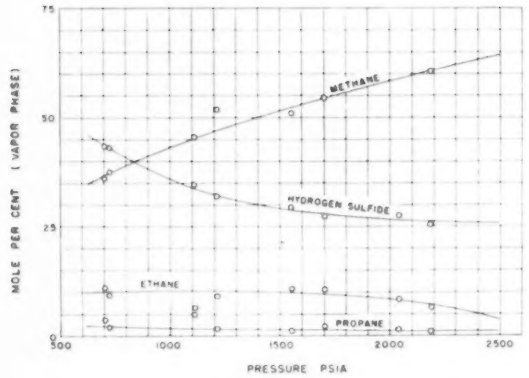

FIG. 5A — COMPOSITION OF LIBERATED GAS VERSUS PRESSURE.

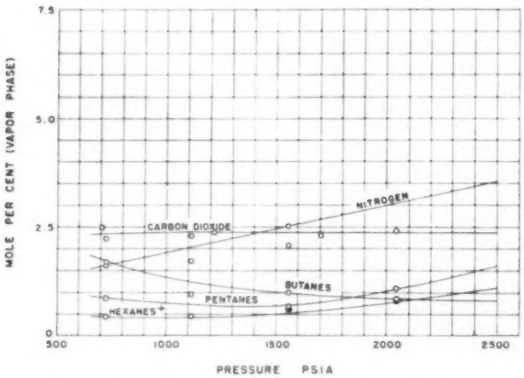

FIG. 5B — COMPOSITION OF LIBERATED GAS VERSUS PRESSURE.

TABLE 4 — COMPOSITION OF LIBERATED GAS*

	RUN NO. 1 PRESSURE PSIA					RUN NO. 2 PRESSURE PSIA				
Component	2187	1702	1215	705	705 - ATM	2043	1554	1111	726	726 - ATM
N_2						9.37	2.51	1.73	1.63	0.68
H_2S	25.6	27.7	32.3	43.9	59.5	27.69	29.58	34.71	43.38	69.48
CO_2	2.1	2.3	2.4	2.5	2.3	2.41	2.08	2.31	2.23	1.46
C_1	60.7	54.8	52.1	36.3	16.1	47.59	51.25	45.88	37.69	9.66
C_2	6.8	10.6	9.7	11.1	10.9	8.57	10.89	6.59	9.95	9.01
C_3	1.2	2.4	1.7	3.7	4.4	1.59	1.31	4.95	2.07	3.63
C_4						0.86	1.00	2.40	1.71	3.46
C_5						1.09	0.69	0.96	0.89	1.72
C_6+						0.83	0.69	0.47	0.45	0.90
Mol. Wt.						26.11	25.51	27.56	28.21	34.48
Sp. Gr.						0.901	0.881	0.952	0.974	1.19

*Experimental data. See Table 5 for smoothed data used in calculating equilibrium vaporization ratios.

composition determinations were made, the first of which showed scattered results for the heavier components because of the small concentrations present. A second determination was made on a considerably larger initial charge and these data were believed to be more accurate. The first determination verified the data of the second for the lighter components and for hydrogen sulfide, so both sets of points are presented in Figs. 5a and 5b for methane, ethane, carbon dioxide, propane and hydrogen sulfide. These data were smoothed in order to calculate the equilibrium vaporization ratios. The smoothed data are presented in Table 5. The second column in Table 5 represents the experimentally determined liquid composition at atmospheric pressure. All other liquid compositions in the table were calculated as described above. These calculated liquid compositions are plotted in Figs. 6a and 6b as a function of pressure.

The smoothed data were used to calculate equilibrium vaporization ratios K following the procedure outlined above. The calculated values are presented in Table 6 and Fig. 7. The solid lines drawn between 10 and 100 psia in Fig. 7 represent the ideal K's for each component, based on fugacities.[12] The data obtained here should approach these lines at low pressures. Therefore, the ideal K's were used as an aid in drawing the K curves for each component.

The K values for butanes and pentanes are quite scattered. This is undoubtedly a result of the fact that the concentrations of these components were of the same order of magnitude as the experimental accuracy. This was also the case for nitrogen; the nitrogen data are not presented in Fig. 7 because of their questionable accuracy.

The position of the K curves for butanes and pentanes was difficult to determine. The curves shown were based on the ideal K's at atmospheric pressure and the trends indicated by the other components of the system, as well as the experimental data.

An analysis of the procedures indicates several possible sources of error which should be considered. One of these is in the determination of the evolved gas volumes. Repeated experiments[9] have shown that gas volumes can be reproduced within 20 cc by means of the brine displacement method. Since the gas volumes involved in this study were of the order of 3000 cc, the maximum error here should be somewhat under 1 per cent.

A second possible source of error is in the determination of the volume of residual oil following the differential gas liberation. This error was kept at a minimum by calibrating the PVT cell for liquid hang up previous to the study. The actual residual oil volume was determined by weighing the displaced liquid and then weighing a small sample in a pycnometer to determine its density. The total weight and density of the residual were used to determine the volume of residual oil. This volume was then corrected to 60°F.

A third source of error to be considered is the entrainment of liquid in the gas phase. Slow displacement from the PVT cell kept this at a minimum. At the end of the liberation no oil was noted on the water surface in the brine bottle. To prevent gas from dissolving to any large extent in the brine, the sample was transferred to the LTD apparatus immediately after the volume was determined. The results of the LTD analysis are believed to be accurate within one mole per cent.

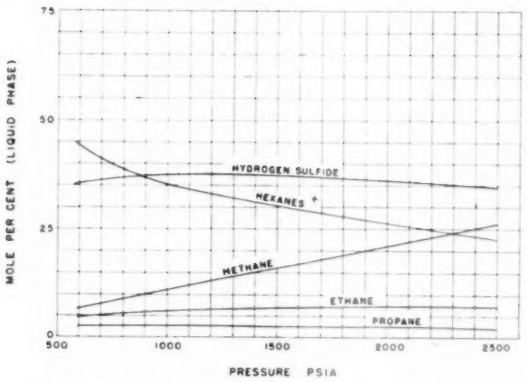

FIG. 6A — CALCULATED COMPOSITION OF SATURATED LIQUID VERSUS PRESSURE.

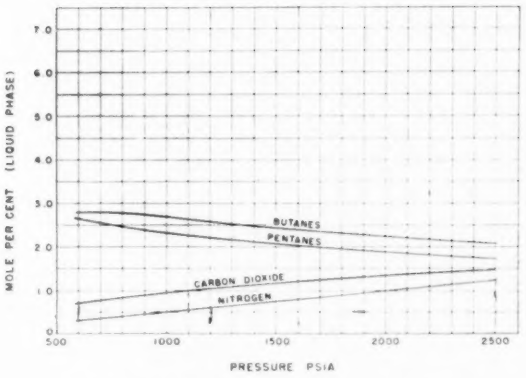

FIG. 6B — CALCULATED COMPOSITION OF SATURATED LIQUID VERSUS PRESSURE.

TABLE 5 — VAPOR-LIQUID COMPOSITION DURING LIBERATION OF DISSOLVED GAS FROM RESERVOIR FLUID, MOLE PER CENT

	PRESSURE PSIA											
	Atmospheric		726		1111		1554		2043		2500	
Component	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	
C_1	0.00	13.80	7.787	37.58	12.10	45.86	16.843	53.23	21.723	56.73	26.121	
C_2	0.00	9.50	5.361	10.15	6.05	10.49	6.677	9.94	7.127	8.08	7.247	
C_3	1.37	4.00	2.854	2.06	2.74	2.04	2.641	1.60	2.497	1.45	2.366	
C_4	2.00	3.45	2.818	1.71	2.66	1.34	2.473	1.00	2.270	0.84	2.090	
C_5	3.63	1.70	2.541	0.88	2.30	0.74	2.081	0.68	1.888	1.04	1.782	
C_6+	92.23	0.87	40.677	0.44	34.86	0.48	30.023	0.64	25.971	0.83	22.812	
H_2S	0.77	64.55	36.761	43.28	37.70	34.60	37.267	29.06	36.135	25.72	34.827	
CO_2	0.00	1.45	0.818	2.27	1.03	2.36	1.216	2.36	1.374	2.33	1.494	
N_2	0.00	0.68	0.383	1.63	0.56	2.09	0.779	2.49	1.015	2.98	1.261	

Atmospheric liquid compositions determined experimentally.
Vapor compositions are smoothed data from Fig. 5a and 5b.
Bubble point liquid (2500 psia) composition determined by extrapolation.

Considering these sources of error, it is believed that the data meet engineering requirements.

Fig. 8 gives a comparison of the results obtained here with the results of Jacoby and Rzasa. Jacoby and Rzasa worked with samples of crude oil containing five mole per cent hydrogen sulfide which they subjected to flash liberation. Their data, Fig. 5, were obtained at a temperature of approximately 150°F, compared with 154°F used in the present study. Since only one temperature was examined here, it was not possible to correct for the temperature difference of four to five degrees between the two studies. It is believed, however, that this difference should not affect the comparison appreciably. From the data given it appears that the higher concentration of hydrogen sulfide in the mixture studied here, raised the K values of the ethane and hydrogen sulfide and lowered those of methane. This effect may be partly the result of the high concentration of relatively volatile components in the mixture (ethane hydrogen sulfide, propane).

Fig. 9 shows a comparison of the results of this study with those of Katz and Hachmuth[2] for hydrocarbons. Here, too, the addition of hydrogen sulfide raised the equilibrium vaporization ratios of the ethane and heavier components.

TABLE 6 — EQUILIBRIUM VAPORIZATION RATIOS FOR RESERVOIR FLUID AT 145°F

	PRESSURE (PSIA)			
Component	726	1111	1554	2043
C_1	4.826	3.790	3.101	2.612
C_2	1.893	1.734	1.489	1.133
C_3	0.722	0.745	0.606	0.581
C_4	0.607	0.504	0.404	0.370
C_5	0.346	0.322	0.327	0.551
C_6+	0.011	0.014	0.021	0.032
H_2S	1.177	0.918	0.780	0.712
CO_2	2.775	2.291	1.941	1.696
N_2	4.256	3.732	3.196	2.936

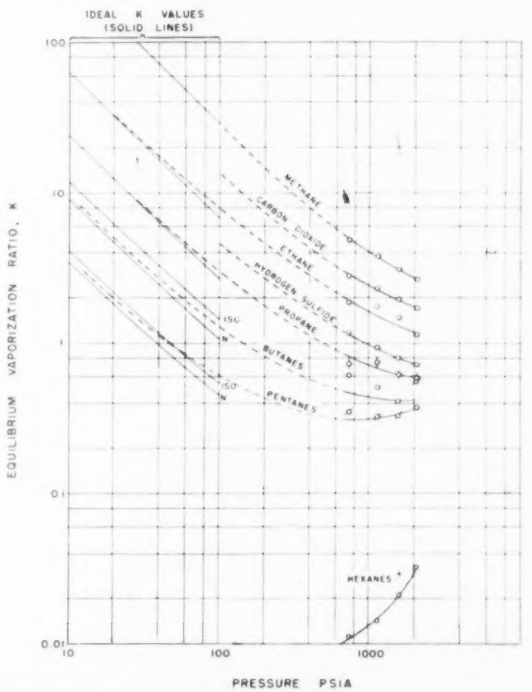

FIG. 7 — EQUILIBRIUM VAPORIZATION RATIOS VERSUS PRESSURE AT 154°F.

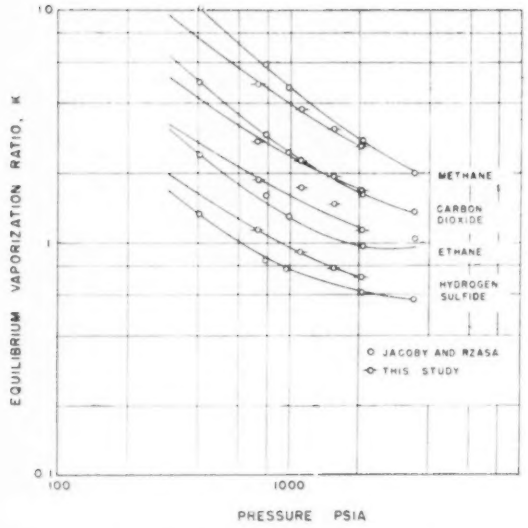

FIG. 8 — COMPARISON OF *K* VALUES FOR RESERVOIR FLUID AT 154°F WITH JACOBY AND RZASA'S DATA AT 150°F.

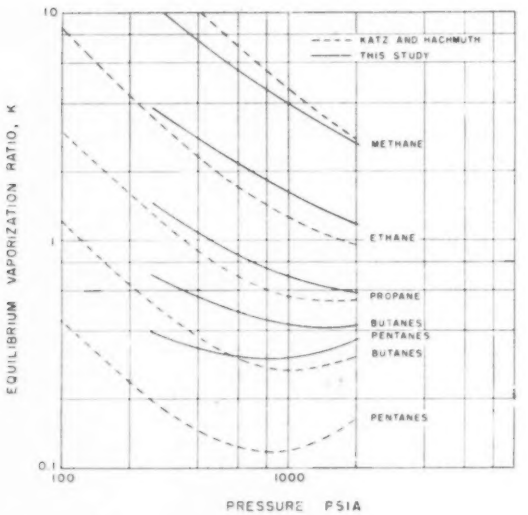

FIG. 9 — COMPARISON OF *K* VALUES FOR RESERVOIR FLUID WITH KATZ AND HACHMUTH'S DATA FOR HYDROCARBONS AT 154°F.

Reamer, Sage and Lacey's *K* values for the methane-hydrogen sulfide system[8] at 160°F fall between those of the present study and those of Jacoby and Rzasa.

CONCLUSION

Equilibrium vaporization ratios were obtained for a system containing 35 mole per cent hydrogen sulfide. The high concentration of hydrogen sulfide has a pronounced effect on the equilibrium vaporization ratios of the other components. It is recommended that in reservoir studies involving fluids of this nature experimental results be used exclusively. In the event these are not available, great care should be exercised in choosing *K* values.

ACKNOWLEDGMENT

The author wishes to thank the management of The Pure Oil Co. for permission to present this paper. Many thanks are also due the analytical group of the Research and Development Laboratories who performed the LTD analyses. The author also wishes to thank K. M. Watson for his valuable assistance in the interpretation of the data presented.

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THE CORROSION-METALLURGICAL ASPECTS of SUCKER RODS and their OIL WELL SERVICE PERFORMANCE

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ABSTRACT

The mechanisms of corrosion and corrosion fatigue damages to sucker rods are examined from a fundamental electrochemical viewpoint, and the relationships of sucker rod microstructures to these damaging effects are defined. The common corrosive agents in crude oil production and storage are discussed as to types of attacks that they cause. The variations of fatigue strength with alloy content, surface preparation, and stress ranges are analyzed. Finally, conclusions are drawn as to how microstructures largely influence and control sucker rod performance.

INTRODUCTION

Greater than 90 per cent of the crude oil produced by artificial lift methods is produced through sucker rod pumping systems. In the USA each year more than $14 million is spent for sucker rods in new and old pumping installations. It is important to make this investment a wise one.

Essentially, the sucker rod system is a long series of steel rods, operating under alternating stress loadings and under mechanical vibrations, which connect the surface power source with the subsurface pump. These rods often operate in a variety of corrosive media, including water, brines, carbon dioxide, hydrogen sulfide, and air.

Basically, this paper is concerned with the problem of the behavior of certain steels in various corrosive media under high and dynamic stress patterns. The main objective of this paper is to show how, once the stress effects and the corrosive environments are defined, one can still realize structural control and beneficial influence upon corrosion and corrosion fatigue.

FUNDAMENTAL DEFINITIONS AND ANALYSIS

In the corrosion and stress behavior of this solid state mixture of iron and iron carbide called steel, one must analyze upon what major factors does its service life depend and of what, exactly, is steel composed. The former question can be referred to two *external* factors and two *internal* factors. The two major *external* factors are:

1. the nature of the stress patterns — size and range of stresses present
2. the nature of the corrosion — erosion environment — the corrodent and/or wear involved

The two fundamental *internal* factors that govern the strength and useful life of a steel both in normal duty and in heavy-duty corrosion service are:

1. the nature of the steel volume properties
2. the nature of the steel surface properties

For the latter question normal steel is defined as a solid mixture of iron and iron carbide particles, generally with certain accidental and intentional elements present. (The amount of iron carbide present is determined by the carbon content of the steel.) These additional elements generally dissolve into either the iron (ferrite) or the iron carbide (cementite) components.

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office Sept. 3, 1953. Paper presented at the Petroleum Branch Fall Meeting in Dallas, Tex., Oct. 18-21, 1953.

Publication space did not permit more metallographic data and examples to be printed. These examples may be seen in the AIME 1953 preprint of this paper or may be secured from the authors.

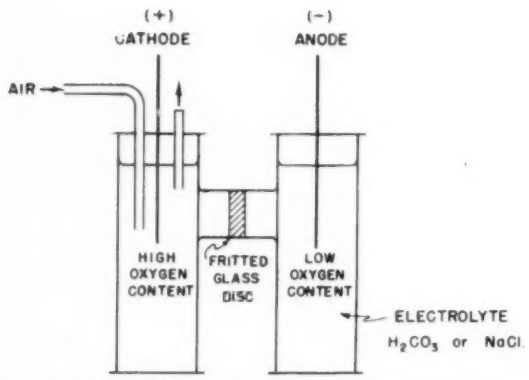

FIG. 1 — THE ELECTROCHEMICAL BASIS OF NORMAL RUSTING OF STEEL.

By changing the size, shape, distribution, number, and composition of the iron carbide particles and of the iron particles, the normal mechanical properties of steels can be changed to produce many desirable combinations. Nearly all the mechanical properties of a normal steel can be defined by changing the nature of the iron-iron carbide mixture or, in other words, its form, composition, and distribution. It is considered that by separating the major variables in this fashion their individual roles and then their various combinations of practical interest can first be assessed.

STRESS AND STRESS RANGES — HOW THEY AFFECT SERVICE LIFE

In the determination of the effects of certain alternating stresses upon air fatigue test specimen life, it is found that below a certain stress level the working life of a specimen is unlimited for all practical purposes. This stress level is called the endurance limit or the fatigue limit.

This limit defines for the given steel, with a certain surface condition and finish, the maximum loadings which may be given the steel in air and yet not experience failures within a reasonable and defined period of service life. An important point is that in corrosive environments there is no real endurance limit but only a steady decrease of the stress required to induce failure as the number of cycles is increased.

Several points of interest need to be underscored. One is that the air fatigue strength is approximately one-half of the air tensile strength value, assuming that the surface conditions and stress conditions of the engineering application and the test specimens are quite comparable.

The second is that corrosion exposures, such as to salt water or salt water and hydrogen sulfide, may bring nominal endurance limits to one-fifth and one-seventh of the tensile values, respectively. These data are, of course, approximations of the endurance limit decreases involved.

The third major point is that the increase of the tensile strength of the steels employed does not offer major hope of substantial improvement of working life. The final point is that one cannot expect any practical stress level to give, in a corrosive environment, an infinite fatigue life, as is inherent in the statement that corrosion is taking place.

Two important engineering considerations here are (1) since sucker rods are imperfect of surface finish and are not comparable to the fatigue test specimens, their performances should be, in fact, somewhat inferior to the experimentally determined values and (2) since a fatigue curve is not an absolute or final curve, but really is but one curve out of a statistical grouping or a family or band of curves, one must expect an endurance limit to be similarly subject to experimental scatter. These two criteria show that one can expect important positive or negative laboratory departures and even larger negative field departures from any non-statistical, single run endurance limit determination.

The effects of stress ranges and types of stresses present are summarized in the empirically established formulas given below:

Gerber's Law Criterion of Stress Range[3]

$$R = R_o\left(1 - \frac{M}{f}\right)^2 \quad \ldots\ldots\ldots\ldots \quad (1)$$

R = safe range corresponding to mean stress M
R_o = safe range when $M = 0$
f = ultimate strength of the material

Moore's Statement of Nature of Stresses[3]

$$S_{max} = S_e\left(\frac{3}{2-r}\right) \quad \ldots\ldots\ldots\ldots \quad (2)$$

If completely reversed stresses are not present in the fatigue test but only repeated cycles of pure tensile of compressive stresses, or tensile-compressive cycles partially reversed, then:

S_e = endurance limit for a given number of cycles for completely reversed stresses
r = ratio of minimum to maximum stress during a cycle, being a negative for completely or partially reversed stresses
S_{max} = endurance limit for this given number of cycles of this pattern of stresses

Strictly speaking, the above formulas apply to steels in air fatigue, but they should also in principle apply to corrosion fatigue. One may realize from these empirical formulas that air fatigue life is improved if the stress ranges are reduced and if the stresses are kept as pure and as unmixed as possible. Any design or operation variables that help in achieving these two points can be expected to help improve performance life.

The effects of frequency of stresses upon fatigue life are considered in a later section.

CORROSIVE AGENCIES

Four corrosive agencies are most commonly of major concern to oil field corrosion losses, being atmospheric oxygen, the dissolved acid gases of carbon dioxide and/or hydrogen sulfide, and the lower fatty acids.

ATMOSPHERIC CORROSION

Atmospheric oxygen, if permitted access to oil well brines or any suitable electrolyte, gives rise to oxygen concentration cells. The corrosion of a buried rusty nail or a rusty tin can or the exposed hull of a ship or the compartments of an oil tanker is of this type and mechanism. The origin of the electrochemical potentials involved here are from the differenences in oxygen content of the anode and of the cathode electrolyte regions, these being due to air accessibility differences.

Fig. 1 illustrates the origins and nature of this EMF. The larger the differences of the oxygen concentration levels at the two electrodes, the larger the produced

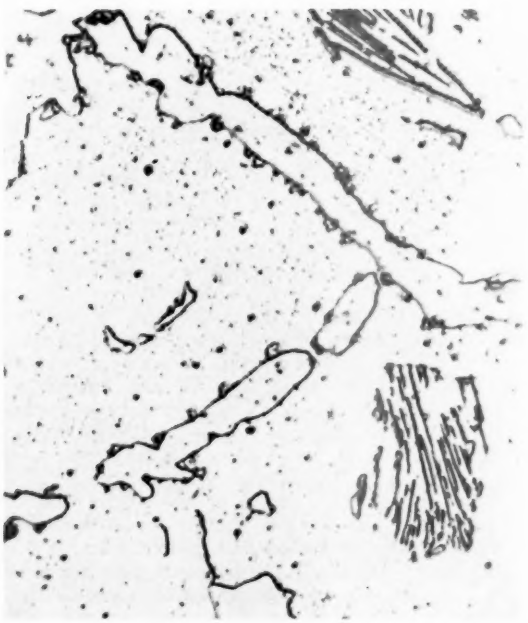

FIG. 2 — THE METALLOGRAPHIC STUDY OF RUST NUCLEATION ON STEEL. THIS SHOWS HOW THE RUST PARTICLES GROW ON THE IRON-IRON CARBIDE INTERFACE.

current will be and the greater the corrosion losses. The electrochemical reaction mechanisms of steel in sea water-oxygen exposures are summarized below:

1. $Fe^{+2} + 2OH = Fe(OH)_2$ (white)
2. $Fe^{+3} + 3OH = Fe(OH)_3$ (yellow-red)
   The reaction mixture is first bluish, then becomes greenish, and finally becomes yellow-brownish as more and more oxygen is absorbed.
3. $2\,Fe + 3O + H_2O = 2\,(FeO(OH)$
   (β—lepidocrocite)
4. $Fe + 3O = Fe_2O_3$ (haematite)
5. $Fe_3C = Fe_3C$ (undecomposed)

From these reactions it may be seen that ordinary rust is not a simple substance but is often a complex material. The sea water, marine, or brine variety is mainly β—lepidocrocite (FeO(OH) with iron carbide being entrapped undecomposed, often with a haematite undercoat film present. The important feature of the oxygen concentration cell is that it is chiefly due to an externally caused EMF. It may proceed somewhat independently of microstructural differences. The fact that it is still partly dependent on microstructure may be noted in that careful X-ray spectrometer and chemical analyses both reveal undecomposed, pyrophoric iron carbide present in ordinary steel rusts.

Evidently iron carbide has a significant role even in the atmospheric corrosion of steels, as may be studied in Fig. 2. Two roles appear for the iron carbide: first, it evidently helps to nucleate the first rust nuclei; then it produces with a given electrolyte an iron-iron carbide EMF which, upon an anodic region of the steel, is additive to the oxygen concentration cell EMF operative thereon. Using ASTM sea water as the electrolyte, the maximum oxygen concentration cell voltage observed with air saturation was greater than 260 mv and with oxygen bubbled in this was greater than 280 mv.

One interesting and significant aspect of the oxygen concentration cell involving iron or steel is that on its local cathodes in sea water or salt water a very tenaceous and protective film of homogeneous haematite is formed. The authors have found that this nonconductive film prevents further corrosion attack and is present in areas which are under cathodic protection. Furthermore, the authors have successfully electrochemically synthesized this desirable film on steels. It is believed that this film may have a direct beneficial action on the corrosion cracking improvement in mild steels under cathodic potential, as noted by R. N. Parkins.[3] As such, it implies that most substantial corrosion fatigue improvements may be accomplished upon steels in sea water and air by application of cathodic protection, even as to prevent or minimize paravane line failures and bridge wire deterioration and premature drill pipe failures. It would be applicable for stressed steels in these corrosive environments, either under constant or repeated stress.

HYDROGEN SULFIDE, CARBON DIOXIDE, AND LOWER FATTY ACID ATTACKS

The anaerobic corrosion attacks found in oil wells are generally due to these gases which form weak acids and the lower fatty acids in produced waters or brines. It is these electrolyte systems that shall be referred to in the remainder of this paper. Only the corrosion tendencies of the metal structures are considered, as the chemistry forms another subject paper.

Two factors tend to influence and control the corrosion behavior of steels in these environments. One is the degree of surface protection afforded by oil well paraffin deposition and the effects of polar compounds in the crude, since certain paraffin deposits can largely seal off the sucker rods from any extensive corrosion

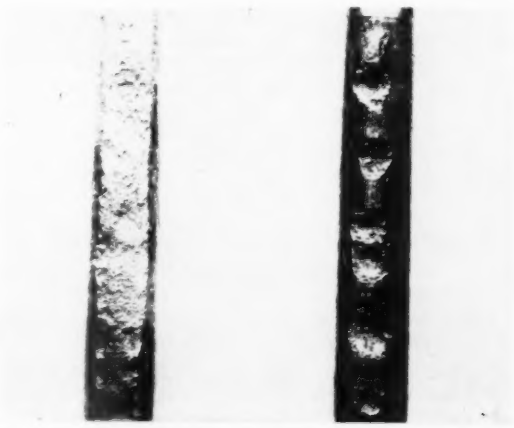

FIG. 3 — THE CHARACTERISTIC CORROSION OF SUCKER RODS, THE LEFT BEING A GENERAL OR UNIFORM ATTACK, AND THE RIGHT BEING A DEEP CONICAL PITTING. AN OIL WELL H_2S-BRINE CORRODENT AT APPROXIMATELY 120°F.

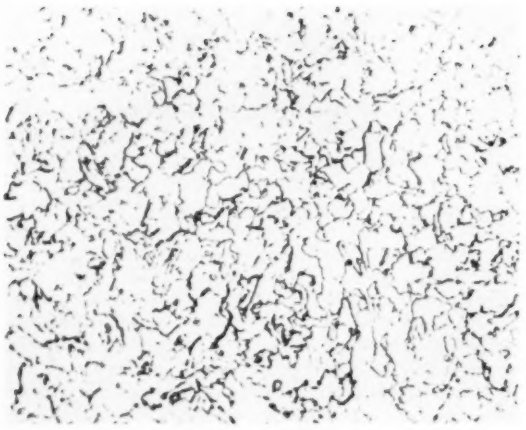

FIG. 4 — THE MICROSTRUCTURE OF THE UNIFORMLY CORRODED SUCKER ROD, 3.5 PER CENT NICKEL TYPE.

attacks and the polar compounds make the surface oil wet, thus excluding the corrosive water. The other is the amount of direct erosion or wear, which may largely determine the protectiveness of the corrosion by-products' films.

In Figs. 3, 4, and 5, one may see the effects of microstructure in sucker rod steels, in combination with wear, upon the character and extent of the corrosion attack in an H_2S-brine at approximately 120°F. It is strikingly interesting to note that, even in spite of a poor microstructure of the banded steel rod with the conical pits, the direct macrocorrosion of areas not subject to erosion wear was not accented.

There appears to be a strong difference of behavior of the hydrogen sulfide and the carbon dioxide attacks upon steels in oil well environments. In "sour" areas wherein hydrogen sulfide-brine electrolytes produce a black iron sulfide film, this insoluble sulfide film tends to be deposited and to be protective. In "sweet" oil areas wherein carbon dioxide-brine electrolytes occur, the corrosion by-product film is not observable and the solubility of the iron bicarbonate usually formed does not permit an insoluble by-product film. No major corrosion resistance may be expected in this type of service, assuming a given structure, unless the insoluble iron carbonate is formed and deposited. In a real sense, it is clear that the nature of the corrosion is, for a given steel and microstructure, the product of the environment, the steel structure, and the corrosion by-product behavior.

THE RELATIONSHIPS OF CORROSION AND MICROSTRUCTURES

From metallurgical studies of the corrosion pitting of the above specimens, we concluded that:

1. The corrosion attack was pearlite-accented and that certain of the pearlitic areas were more anodic in the ferrite-pearlite aggregate.
2. The iron-iron carbide potential was the agency helpful to and effective in the control of the attack. Preliminary potential measurements show that this EMF is greater than 250 mV and may be as high as 300 mV in 0.1 N NaOH at 73°F.

To demonstrate this point, it was found that in any similar series of steels arranged in order of carbon content the higher carbon steels were clearly cathodic to the lower carbon steels and that a 1.80 per cent Ni — 0.21 per cent C — 0.28 per cent Mo sucker rod (case-hardened) coupling was cathodic to the identical steel not carburized.

From the published data of S. M. Jones Co. on endurance limits of three popular sucker rod types,[4] a study was made of the relationships of the endurance limits of these three steels as a function of carbon content. A direct, linear, characteristic relationship was found between the carbon content and the endurance limit. While these endurance limits must be qualified by the previous considerations, the general relationship evident is considered interesting. It can be noted that the function of the nickel content here is to act as a ferrite strengthener and that its corrosion contribution with these small additions is to permit lower carbon contents to be used, and it cannot be held responsible for the corrosion fatigue improvements noted.

From the literature study, it was found that E. Heyn and O. Bauer[5] first studied the effects upon corrosion losses of carbon content and form. It was found that C. Chappell[6] demonstrated the increase of corrosion rates of steels wth increase of carbon content, showing that the corrosion losses decreased with this order: quenched, tempered, normalized, rolled, and annealed. Significant contributions on the above topics were made by H. Endo[7] and T. Matsushita and K. Nagasawa.[8]

In the work of T. Hoar and D. Havenhand,[9] massive cementite was considered to behave cathodically. F. Prange,[10] in a 1946 review article, made the observation that the iron-iron carbide potential could be considered as being relevant to the corrosion of steel. R. W. Manuel[11] has demonstrated experimentally the effect of certain carbide forms upon corrosion losses. He proved that the number and form and distribution of the iron carbide in steels are important to the accelerated, continuous corrosion of steels as affecting both the geometry of the corrosion and the weight loss rates.

Finally, the experimental data of C. Larrabee[12] show that, while phosphorus (primarily) and copper (sec-

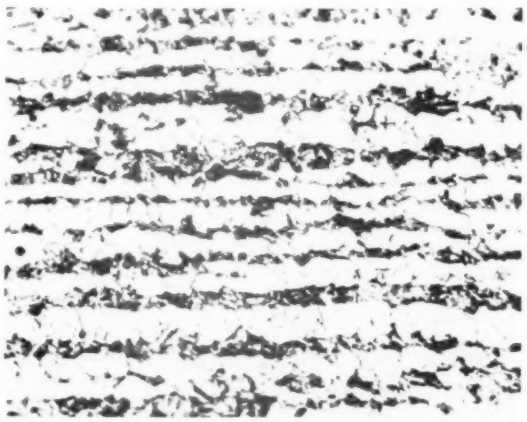

FIG. 5 — THE INJURIOUS MICROSTRUCTURE OF A BANDED NICKEL STEEL SUCKER ROD, 1.75 PER CENT NICKEL. THIS BANDED STRUCTURE WAS RESPONSIBLE FOR THE CONICAL, DEEP PITTING.

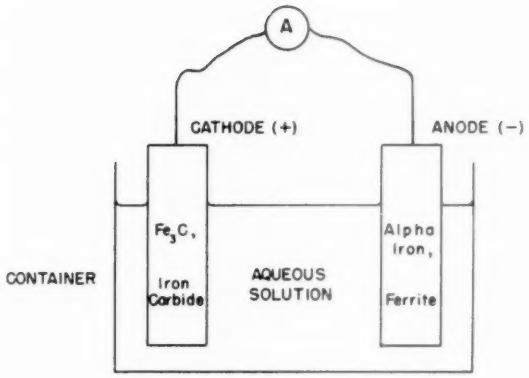

FIG. 6 — THE FUNDAMENTAL BASIS FOR THE ELECTROLYTIC MICRO CELL CORROSION OF STEEL. THIS CELL REPRESENTS ONE PAIR OF ELECTRODES PRESENT IN PEARLITE, SPHEROIDITE OR OTHER FERRITE-CARBIDE AGGREGATE.

ondarily) are atmospheric corrosion retardation agents, it is the carbon content of structural carbon or structural alloy steels that is the primary corrosion acceleration agency.

In the metallographic studies of 1.75 per cent Ni steel mentioned, the surface of the corroded steel was found to be preferentially attacked at the pearlite grains, some of which were found to be indented by the corrosion. The pearlite grains of different orientations were corroded to varying depths. This preferential attack of the pearlite grains was also observed shortly afterwards in oil well tubing and casing, where the pearlite, being more uniform, and the grain size, being much larger, made the observations more certain and accurate.

Consequently, the authors were led to consider that the corrosion of these normal steels was taking place through the formation of local microelectrolytic cells by having the iron carbide (cementite) platelets of these steels to function as one microelectrode, while the alpha iron (ferrite) platelets served as the other. Figs. 6, 7, and 8 afford a description of this electrochemical behavior of the normal microstructural elements and forms in normal steel as determined from our laboratory experiments and observations of field experience. It was observed that:

1. The corrosion of the pearlite was orientation dependent (as determined from the pearlite orientation in reference to the corrosion medium or, equivalently, to the number of cells active per unit area of exposed surface).
2. The corrosion of ferrite-carbide aggregates was not orientation dependent, giving rise to more uniform and severe corrosion activity, while the pearlitic corrosion tended to give restricted pitting action because of the poorly oriented grains.

These points can be clearly seen by examination of Fig. 9. It may be observed that the grain size found in a pearlitic steel is important, since it determines the magnitude and nature of the pearlitic corrosion pitting actions and so the local stress-raising effects.

HOW SUCKER RODS FAIL

One other point needs to be considered before the signifiicance of the iron-iron carbide potential and its orientation dependence in pearlite and orientation independence in spheroidite or globularized iron carbide forms can be assessed. *What is the mechanism of corrosion fatigue failures in sucker rods?*

Laboratory experience, from the macro and micro investigations of many failure specimens, shows that the initiation and the growth and development of a corrosion fatigue failure are essentially clearly intergranular until the stress levels reached on the remaining areas are so high that the normal tensile-type failure occurs. For approximately 60 to 90 per cent of the specimen area, the intergranular failure takes place with little or no local elongation. Then, transgranular or tensile failure takes place with slipping, warpage, and elongation of the grains being noted. These failure mechanisms can be observed by macrostructure studies alone.

These failures are quite similar to high-temperature failures in high-temperature alloys and in jet engine alloy blades. First, there is a chemical oxidation and reaction and penetration of the grain boundaries with a chemical deterioration and rupture of the grain boundaries. Then there is the normal transgranular tensile type failure (with perceptible elongation) when excessive stress levels are reached.

In the authors' judgment, in corrosion fatigue, the proportion of the intergranular to the transgranular fracture components depends upon the ratio of the stress level actually experienced to the yield stress level. It is, therefore, an index of the quality of design and its safety factor. The authors' data, therefore, force the conclusion that the condition of the grain boundaries and the chemical composition of the grain boundaries, as to possible electrochemical action, are important and even critical as to corrosion fatigue behavior. (The authors' data further imply that there does not exist in fact an "equi-cohesive" temperature for metals.) Fig. 10 illustrates a condition in the cor-

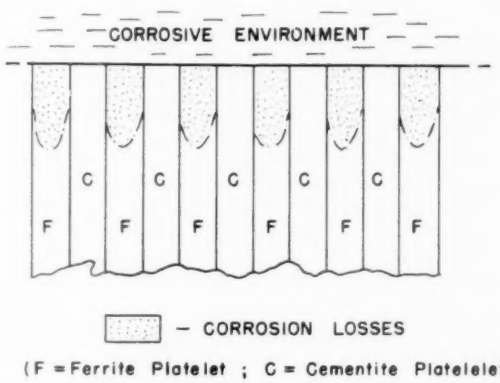

FIG. 7 — A BASIC MECHANISM IN THE CORROSION OF STEELS: THE ORIENTATION-DEPENDENT CORROSION OF PEARLITE (A STEEL MICROSTRUCTURAL FORM WITH ALTERNATING PLATELETS OF IRON AND IRON CARBIDE).

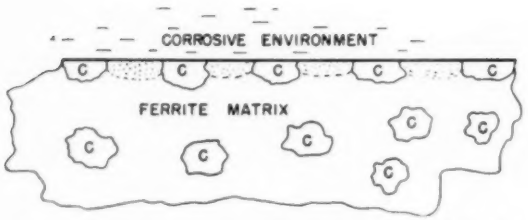

FIG. 8 — A BASIC MECHANISM IN THE CORROSION OF STEELS: SPHEROIDITE OR FERRITE-CARBIDE (PARTICLE SIZE AND DENSITY DEPENDENT, ORIENTATION INDEPENDENT) CORROSION.

rosion fatigue failure mechanism, found only in one mode, the electrochemically-produced one, of the general grain boundary oxidational failure mechanism in metals and alloys.

Fig. 11, included as a graphic example, illustrates the intergranular HF stress corrosion cracking of *K* monel. It is seen that in a grain boundary which possesses iron carbides there already exists on a microelectrolytic cell basis an ample supply of local anodes and cathodes. The intergranular corrosion of certain 18 Cr-8 Ni stainless steels may be considered to be an analogous case. The authors believe that these grain boundary carbides in mild or low carbon steels are instrumental in corrosion fatigue work and are the primary agency in the lowering of the endurance limit with increased carbon content. The presence of iron carbide particles at the grain boundaries may have a multiple effect. Besides the electrochemical effects of dissimilar structures being present, the presence of a second phase at the grain boundaries also means the presence of severe microstresses. These microstresses may be expected to make the grain boundary even more anodic in these systems.

The results obtained in R. N. Parkins' work,[11] wherein he shows the improvement of stress corrosion cracking resistance of mild steels (0.07-0.22 per cent carbon) due to minimization of grain boundary cementite envelopes may be interpreted as being due to the focusing of anodic action upon the grain boundaries by the presence of grain boundary iron carbides.

THE DESIGN AND SELECTION OF SUCKER ROD STEELS

With the source of the microelectrolytic cell EMF being considered (the iron-iron carbide EMF) and with the nature of the failure being recognized as intergranular, it becomes relevant to examine the merits of various possible variations in microstructure.

First, the volume and the grain boundary resistance to deterioration should be made a maximum. With pearlitic steels, this implies a preference for reduction of corrosion pit notching through making the grain size as fine as is reasonably possible. It also implies that the carbides per unit grain boundary area be minimized.

Second, it appears evident that as low a carbon content is desirable as is consistent with necessary yields and elongation values.

Third, whatever the given carbon level, it should preferably be volume-distributed rather than grain boundary-distributed. This generally means a spheroidized carbide distribution rather than a pearlitic platelet distribution.

Fourth, it is clear that, while quenched and tempered structures have no built-in macro-corrosion resistance possible from orientation, it is quite possible to obtain some corrosion resistance based on orientation benefits from pearlite aggregates. But here a certain difficulty creeps in. The pearlite grains always have partial grain boundary cementite envelopes (Fig. 12). The pearlite grains are nucleated from grain boundary cementite particles so that it appears that the pearlite's macro-corrosion resistance can be obtained only at the expense of corrosion fatigue resistance (because of poor micro-corrosion resistance at the grain boundaries). This grain boundary cementite envelope effect works to minimize the pearlite orientation effects, since a poorly oriented grain may be protected initially by a coherent grain boundary cementite envelope.

The work of Dolan and Yen[14] on air fatigue indicates precisely this point, if the differences of the yield strengths of their steels can be assumed to be negligible. (Actually it appears more reasonable to express endurance limit in terms of yield strength than tensile strength.)

Several conclusions are possible from these reasonings: One is that Hopkinson's view,[15] that a slight increase of endurance limit should result with an increase of frequency of stress reversals, must be even more true for corrosion fatigue than for air fatigue. Since the electrochemical oxidation of the grain boundaries is a time dependent process, the lower the stress application frequency the larger the net effect of corrosion

FIG. 9 — AN EXAMPLE OF THE LOCAL MICRO NOTCHES DUE TO PREFERRED PEARLITE CORROSION REACTION.

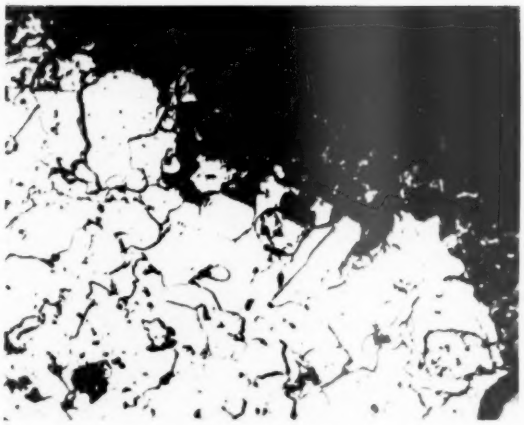

FIG. 10 — THE GRAIN BOUNDARY FAILURE PATH SHOWING GRAIN BOUNDARY CRACKING AND PARTING AND NOT SHOWING LOCAL GRAIN DEFORMATION.

penetration should be. But the effects of the frequency may not be structure-independent. An increase of frequency may be expected to give an effective increased life to grain boundaries that do have carbides and to have little or no effect upon grain boundaries that do not have carbides or other two-phase systems to give electrochemical differences.

MANUFACTURING VARIABLES AFFECTING SUCKER ROD PERFORMANCE

Several surface condition factors need to be underscored, as the final performance of the sucker rods is dependent upon both the surface and the volume properties of the finished sucker rod. First, the fact that increased surface roughness decreases the air fatigue life of steel is well established.

Second, the presence of mill scale, Fe_3O_4, is undesirable because it is very strongly cathodic to iron and causes strong local microelectrolytic cell action. The authors' results show that the EMF produced by the Fe_3O_4–Fe action is more than 0.82 volt in 0.1N HCl at 72°F. If the mill scale produced in manufacture is quite thick, there is both decarburization of the surface and severe grain boundary magnetite inclusion formation.

Both decarburization and inclusion formation tend to lower the corrosion fatigue life. The former factor, although improving corrosion resistance, tends to lower the net available cross section, while the latter forms a destructive corrosion system. If a pure ferrite film could be formed with a comparable or equal cross section, there should be a marked increase of corrosion fatigue life, as is implied by the reduction of iron-iron carbide cell density. Finally, any surface mechanical or chemical (electrochemical) injury can be expected to accent and intensify corrosion fatigue failures.

The Fe_3O_4-Fe potential referred to in the above paragraph refers to the hydrochloric acid-oxygen system, an aerobic system. In hydrogen sulfide-brine systems (anaerobic) the ferrite reacts rapidly to form an insoluble iron sulfide film. The effect of this film is apparently very desirable, since the mill scale, Fe_3O_4, does not in practice show corrosion acceleration with the iron sulfide. In hydrogen sulfide-brine oil well media, the FeS-Fe_3O_4 potentials are either quite small or are essentially negligible. (The carbon dioxide-brine cases are not defined for the Fe_3O_4 case; here, however, the Fe_3O_4 potentials are expected to be significant.) From the above it is apparent that the normally encountered decarburized steel surface layers, mainly ferrite with some residuals of Fe_3O_4 inclusions, act in certain applications as built-in corrosion inhibitors. These commercial ferrite films, within desirable limits, offer very interesting possibilities for use as desirable corrosion inhibitors for hydrogen sulfide-brine areas.

CONCLUSIONS

1. The performance and life of oil well sucker rods are microstructurally dependent and can be regulated by heat treatments. These variables are subject to manufacturing practice control. For optimum sucker rod service, the structure and carbon content as well as the alloy composition and design loads should be considered for maximum corrosion fatigue life. These should be considered in regards to the particular corrosive environment.

2. The corrosion fatigue life of sucker rods is carbide (carbon) content sensitive as well as carbide distribution sensitive. The grain boundary type of distribution is specifically undesirable. It is believed that the iron-iron carbide potential is the responsible and controlling agency.

3. Corrosion fatigue failures are mainly grain boundary oxidational reaction failures.

4. No external, electrolysis-producing currents are needed to give electrolytic action in steels for oil production service. The "built-in" microelectrolytic cells, from microstructural variations provide ample voltages, under certain conditions, to give corrosion or corrosion fatigue attacks. The amount and form and distribution of the iron carbide help to control these.

5. It is pointed out that the iron-iron carbide potential is apparently of first-order significance even for normal rusting or atmospheric rusting. Atmospheric rusting

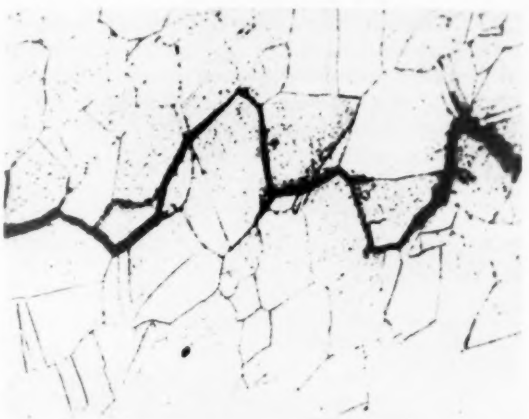

FIG. 11 — THE GRAIN BOUNDARY OXIDATIONAL FAILURE OF K MONEL DUE TO HF STRESS CORROSION CRACKING. THIS EXEMPLIFIES THE NATURE OF THE ORDINARY SUCKER ROD FAILURES.

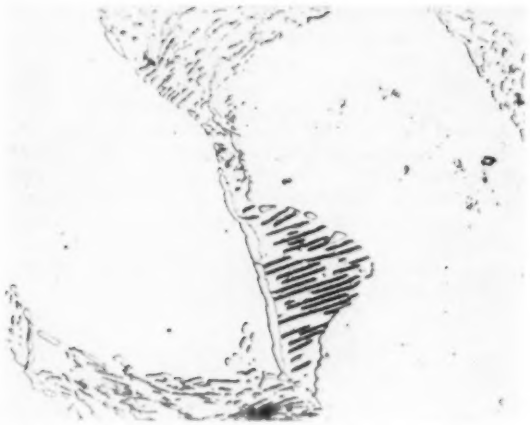

FIG. 12 — THE GRAIN BOUNDARY ENVELOPES OF MASSIVE IRON CARBIDES IN A HIGH PURITY STEEL.

appears to be nucleated at the ferrite-cementite (or iron-iron carbide) interface. In an anodic region of a steel in the atmospheric rusting process, the iron-iron carbide potential is apparently additive upon the oxygen concentration cell potential.

6. The sucker rod life, for a given stress pattern and surface, may be considered as being dependent upon both corrosion resistance and erosion resistance.* Where rod wear is not a problem and where corrosive service is encountered the lower carbon alloy steels of suitable yield strength levels and quenched and tempered structures would seem preferable. Where rod wear is a significant factor, the plain carbon and carbon-manganese rods (normalized condition) would tend to confer a desirable erosion resistance and a certain corrosion resistance, both of which should contribute to an improved corrosion fatigue life for this case. Finally, where neither wear nor corrosive conditions occur the low carbon alloy or the normalized plain carbon and carbon-manganese steels are indicated, with the former giving the longer life or the larger load-carrying capacity.

While corrosion fatigue capacity has been emphasized in this paper the final sucker rod behavior is, in certain cases, dependent on the corrosion-erosion fatigue behavior of sucker rod steels, with the erosion resistance increasing with increased carbon content and structural hardness.

*By erosion is meant rubbing and physical impingement losses.

ACKNOWLEDGMENTS

The authors wish to underline their sincere appreciation of the aid and encouragement given this study by D. A. Shock and to R. G. Edholm for his X-ray spectrometric determinations of β-lepidocrocite, haematite, and iron carbide in various rusts. To the management of Continental Oil Co. we are indebted for permission to publish the results of these investigations.

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☆ . . . *meet the* AUTHORS

JOE S. LEVINE is a member of the research staff at Shell Development Company's Exploration and Production Research Division in Houston. He received his BS degree in chemical engineering from the University of Texas. He continued his studies at Pennsylvania State University, receiving an MS and, in 1941, a PhD degree in petroleum engineering. From 1942 to 1946 he was an officer in the Navy and spent more than half that time as engineering officer on an LST in the Pacific. After being released from active duty in 1946, he joined Shell and has been engaged principally in research relating to the flow of fluids through porous material with particular emphasis on secondary recovery of petroleum.

FREDERICK JOHN RADD is senior research metallurgist in the Development and Research Department of the Production Research Division, Continental Oil Co., Ponca City, Okla. He is a graduate in metallurgical engineering from the Missouri School of Mines and Metallurgy of the University of Missouri. In 1950 he received an ScD degree in metallurgy from Massachusetts Institute of Technology. He has had industrial and laboratory metallurgy experience with U. S. Steel Corp., General Electric Research Laboratories, Massachusetts Institute of Technology, U. S. Army Ordnance Department's Ballistic Research Laboratory, and Boeing Aircraft. In metallurgy, he is most concerned with corrosion fatigue research, and with high temperature behavior of metals, with the general theory of the strength of metals, with the physical chemistry of liquid metal behavior, with age hardening reactions, and with the liquid-solid transformation kinetics.

ROBERT LEE MCGLASSON is a junior research metallurgist for the Production Research Division of the Development and Research Department, Continental Oil Co., Ponca City, Okla. He is a graduate in physics and mathematics from Northwestern State College, Alva, Okla., and a veteran of service in both the Navy and the Marines. Also, he has worked with Boeing Aircraft Co., Wichita, Kan.

HAROLD VAGTBORG, JR., is in charge of PVT studies in the Research and Development Laboratories of the Pure Oil Co., Crystal Lake, Ill. He is a graduate in mechanical engineering from the University of Kansas in 1950. Recently he has completed requirements for a MS degree in petroleum engineering.

Annual Statistics Volume Available

Statistics of Oil and Gas Development and Production, Vol. 7 covering 1952, is now available. This latest volume in the AIME's annual petroleum statistics series contains 704 pages covering domestic and foreign operations during 1952, more than any previous volume.

The data were collected and compiled by authoritative engineers and geologists in all major and most minor oil-producing areas of the world, and took more than a year to assemble for publication. Directing the work was the Petroleum Branch Production Review Committee, headed by R. B. Gilmore, chairman, Milton Williams, vice-chairman for domestic areas, and A. H. Chapman, vice-chairman for foreign developments.

Presented in the same form as previous volumes, data are organized by areas and fields. Production tables include annual and cumulative recovery of oil, gas, and condensate, performance data, reservoir characteristics, number of wells, producing formation and depth, and quality of production. Other tables list individual wells drilled during 1952, both discoveries and extensions, and their depth, formation, and initial production. The most important 1952 developments are summarized in introductory paragraphs to most of the area reports.

The volume may be ordered from the American Institute of Mining and Metallurgical Engineers, 29 West 39th St., New York 18, N. Y. Price is $5 to AIME members and $10 to non-members.

Study Group on Unitization Planned by Dallas Section

Study-group meetings will be held by the Dallas Local Section in April and May. Field Unitization will be discussed at the meetings to be held on the Southern Methodist Universit campus. Approximately 75 attended the first meeting, held in March.

Delta Local Section Hears Report on Gulf Pipe Line

The Delta Local Section heard Charles L. Graves of J. R. McDermott Co., give a paper on the "Resume of Gulf of Mexico Pipe Line Construction to Date and a Look into the Future." at the February meeting.

branch AFFAIRS

PERSONALS

★

FRANK A. NICE, JR., has joined the staff of Hurt Oil Co., Ltd., in Houston as manager of drilling and production operations. A native of Texas, he was graduated from Texas A&M College with a BS degree in petroleum engineering in 1942. He served with the armed forces until October, 1945. Formerly he was associated with Texas Gulf Producing Co. as petroleum engineer in both domestic and foreign operations.

★

KENNETH E. MEYER is now petroleum engineer and analyst for Lehman Corp. (investors), New York. He formerly was with Cities Service in New York.

★

E. G. DODSON has transferred from Caracas, Venezuela, where he was the chief petroleum engineer for the Venezuela Division of the Texas Co. He is now chief engineer for the Texas Co. Foreign Producing Department, with offices in New York City.

★

A. A. HALKERS has accepted the position of district petroleum engineer for British American Oil Co., Ltd., Edmonton, Canada. He formerly was drilling equipment engineer for the Royal Dutch Shell Oil Co., Djakarta, Indonesia.

★

PAUL MCELROY is now petroleum engineer for Three-States Natural Gas Co. in Dallas. A graduate of Texas A & M, he was engineer-in-charge of the Magnolia Petroleum Co. office in Seminole, Tex., prior to accepting his present position.

R. S. OUSTERHOLT has rejoined Dowell, Inc., in Tulsa, after six months absence, during which time he was a partner in MWL Tool Co. He has now sold his interest in the tool company and is the Dowell general offices in charge of sales for oil field and industrial services. He was district sales manager for Dowell in the Midland area before entering private business.

★

CHARLES H. PISHNEY and BURT ATKINSON have established the Pishny and Atkinson consulting firm in Fort Worth, with offices in the Commercial Standard Building. Pishny is a graduate of the University of Chicago. He spent 15 years with Amerada as chief evaluation consultant, and the past 10 years in a consulting capacity. Atkinson, a graduate of Rice, was with Humble for five years in a reservoir engineering and supervisory training capacity. Later, he was a consultant in Midland for two years.

★

D. B. TALIAFERRO and GUY WADDINGTON have received the Distinguished Service Award with Gold Medal, the highest honor of the Department of Interior. The engineers of the U. S. Bureau of Mines Petroleum Experiment Station (Bartlesville, Okla.) received the presentation from Secretary of Interior Douglas McKay.

★

SALEEM TANNOUS has completed his graduate work at Louisiana State University and has accepted a position with the American Independent Oil Co. in Kuwait, Persian Gulf.

★

JOSEPH G. LAMBERT, geological engineer, has joined the staff of Earlougher Engineering, Tulsa. After graduation from Princeton University in 1948, he was employed by Stanolind Oil and Gas Co., in Rangely, Colo., and in Casper and Cody, Wyo., specializing in reservoir engineering. From 1950 until accepting the position with Earlougher, he worked in the Petroleum Department of The Chase National Bank of New York.

★

JUAN F. VILLARREAL is now Dean of the School of Petroleum Engineering, Universidad Industrial de Santander at Bucaramanga, Colombia, South America. He recently received his PhD degree at Pennsylvania State University.

★

CHARLES R. DODSON, formerly of Stanley, Stolz, and Dodson, of Los Angeles, is now petroleum engineer for the National City Bank of New York. A member of the Branch Executive Committee, Dodson has worked with Standard Oil of California (1936-1947), been a member of the University of California faculty, and from 1947 until 1953 was a professor and head of the Petroleum Department of University of Southern California. He holds a BS degree from the University of Maryland and an MS from Massachusetts Institute of Technology in mechanical engineering, plus two additional years of study at the University of California. His New York headquarters is 55 Wall Street.

★

FREDERICK W. SEYFARTH is now serving as a petroleum engineer for Cable Engineering, Wichita Falls, Tex. He formerly was production foreman for Standard Oil Co. of Texas, at Iraan.

branch AFFAIRS

PERSONALS

★

HARRY B. SCHRAMM is now vice-president in charge of engineering and manufacturing of Otis Pressure Control, Inc. He is a graduate of Texas A&M College as a petroleum engineer. Prior to joining Otis in 1946 he worked in north central and west central Texas. Herbert C. Otis, Jr., is the newly-appointed executive vice-president of Otis.

★

CORTEZ P. HACKETT is now Director of Development of the Solvay Process Division, Allied Chemical & Dye Corp. He is a graduate of the Colorado School of Mines and has been with Solvay since 1932. In his new post he heads engineering, research, and construction departments, with his office remaining in Syracuse.

★

T. K. MATTHEWS has joined the Republic National Bank of Dallas as a petroleum engineer in the Oil Department. Since his graduation from the University of Oklahoma in 1949, he has been with Gulf. For the last three years he has been a reservoir engineer in the Fort Worth Gulf offices.

★

JOHN A. NEWMAN has announced the opening of a consulting office in Houston. He formerly was Houston division reservoir engineer and Houston area proration and utilization engineer for Shell Oil Co. Newman will specialize in "reserve estimates and property valuation, development and management of oil and gas properties, regulatory work and allied services." The establishing of the Houston office by Newman follows over a year of private practice in the mid-continent, Ohio, as well as Houston. He is a graduate in chemical engineering of Cornell University.

★

WAYNE E. SWEARINGEN, graduate of the University of Oklahoma in 1948, has accepted a position as petroleum engineer with Herman H. Kaveler, petroleum consultant in Tulsa. He was formerly with Stanolind in the Oklahoma Division Office. Prior to his graduation from Oklahoma, Swearingen spent three years in the Air Corps. He has been primarily engaged in reservoir evaluation, pressure maintenance, and unitization operations in his professional work.

★

FRITZ G. TAVES has been assigned to the staff of Pierre Schlumberger, president of Schlumberger Well Surveying Corp. He will retain his offices in Los Angeles and handle special assignments. Taves has been Schlumberger Pacific Coast area manager for a number of years, having originally joined the corporation in 1935. From 1942 until 1946 the University of California petroleum engineering graduate served as executive officer for the Elk Hills Naval Petroleum Reserve.

★

LEWIS G. WEEKS has been appointed chief geologist of Standard Oil Co. (N. J.). Prior to his new assignment, he was the company's senior research geologist in the Producing Coordination Department. Weeks is a graduate of the University of Wisconsin and did graduate work at Cornell. He started his petroleum geology career in Indian in 1920. Prior to his transfer to New York, he engaged in geological work in many parts of South America, and was president of Standard Oil Co. of Bolivia. He is very active in the AAPG as well as the AIME.

★

MILTON E. LOY has been named manager of the Pacific Coast area for Schlumberger, replacing Fritz G. Taves who has been assigned to the staff of the president. He has been with the corporation for 14 years, having served most recently as assistant to Taves. He is a graduate of the University of California in mechanical engineering and is widely known on the west coast as a meeting speaker.

★

JOHN TOM REYNOLDS has opened offices in Dallas as a consulting petroleum engineer, specializing in property management. For the last three years he has been employed by D. D. Feldman Oil and Gas, Dallas. He is a graduate of the University of Kansas and has worked with Sohio and Halliburton in the Gulf Coast, Mid-continent, and Eastern states.

★

CARL M. SCHWAB is now chief engineer of Otis Pressure Control, Inc. He joined Otis in 1949 and worked in Houston and New Iberia before being transferred to Dallas as administrative manager and liaison director for the home office. He studied petroleum enginering at Texas A&M for three years before transferring to the University of Minnesota for a degree in civil engineering.

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LOCAL SECTION MEETING SCHEDULE

BILLINGS PETROLEUM SECTION: Meets in Billings, Mont. *Chairman*, H. R. Lowe, Wallace & Lowe, Inc., Billings. *Secretary*, J. G. Yapuncich, Yapuncich-Sanderson Lab., Billings.

DALLAS SECTION: Meets third Monday each month in Dallas. *Chairman*, G. R. Brainard, Jr., Lucerne Corp., Dallas. *Secretary*, A. B. Dyes, The Atlantic Refining Co., Dallas.

DELTA SECTION: Meets second Tuesday each month in New Orleans. *Chairman*, A. L. Vitter, California Co., New Orleans. *Secretary*, W. D. Clift, New Orleans.

DENVER PETROLEUM SECTION: *Chairman*, T. O. H. Mattson, The Texas Co., Denver. *Secretary*, A. J. Carter, Jr., Bay Petroleum Corp., Denver.

EAST TEXAS SECTION: Meets second Tuesday each month at Gregg County Airport. *Chairman*, G. L. Scheirman, Shell Oil Co., Kilgore. *Secretary*, T. A. Banta, Lufkin Foundry & Machine Co., Kilgore.

FORT WORTH SECTION: Meets third Tuesday each month in Fort Worth. *Chairman*, M. I. Taylor, Gulf Oil Co., Fort Worth. *Secretary*, B. J. Bonner, T & P Coal and Oil Co., Fort Worth.

GULF COAST SECTION: Meets third Tuesday each month in Houston. *Chairman*, W. B. Hopkins, Gulf Oil Corp., Houston. *Secretary*, Herman A. Engel, Jr., Union Sulphur and Oil Co., Houston.

ILLINOIS BASIN CHAPTER: Meets first Thursday each month in Salem, Ill. (No meetings in July and August.) *Chairman*, Jerry Vaughan, Sun Oil Co., Evansville, Ind. *Secretary*, Harry Bridges, Shell Oil Co., Centralia, Ill.

KANSAS SECTION: Meets second Wednesday in Wichita and fourth Thursday in Great Bend. (No meetings in June, July, and August.) *Chairman*, John T. Gary, Continental Oil Co., Wichita, Kan. *Secretary* R. M. Acher, The Texas Co., Wichita.

LOU-ARK SECTION: Meets third Monday each month in Shreveport, La. *Chairman*, C. R. Olson, Ohio Oil Co., Shreveport. *Secretary*, E. P. Ogier, W. C. Spooner, Inc., Shreveport.

MID-CONTINENT SECTION: Meets second Monday each month in Tulsa: study group meets fourth Tuesday each month (Luncheon meetings each Thursday, Mayo Hotel.) *Chairman*, G. C. MacDonald, Gulf Oil Corp., Tulsa. *Secretary*, F. H. Callaway, Stanolind Oil & Gas Co., Tulsa.

NORTH TEXAS SECTION: Meets second Monday each month in Wichita Falls. *Chairman*, D. B. Meisenheimer, Texas Co., Wichita Falls. *Secretary*, P. F. Chapman, Box 2010, Wichita Falls.

MISSISSIPPI SECTION: Meets in Laurel, Jackson, and Natchez, Miss. *Chairman*, W. I. Sanderson, Halliburton Oil Well Cementing Co., Natchez, Miss. *Secretary*, Bill J. McEver, Lane-Wells Co., Natchez, Miss.

OKLAHOMA CITY SECTION: Meets at noon third Thursday each month in Oklahoma City. *Chairman*, R. K. McIvor, Sohio Petroleum Co., Oklahoma City. *Secretary*, W. C. Pearson, Stanolind Oil & Gas Co., Oklahoma City.

PACIFIC PETROLEUM CHAPTER: Meets in Los Angeles. *Chairman*, Milton E. Loy, Schlumberger Well Surveying Corp., Los Angeles. *Secretary*, J. A. Klotz, California Research Corp., La Habra, Calif.

JUNIOR GROUP: Meets second Thursday each month at Turf Club in Rivera. *Chairman*, J. P. Garten, Long Beach Oil Development Co. *Secretary*, David K. Hayward.

PERMIAN BASIN SECTION meets third Monday each month in Midland or Odessa, Tex. *Chairman*, J. R. Brack, Ohio Oil Co., Midland. *Secretary*, J. B. McClellan, Dowell, Midland.

SAN JOAQUIN VALLEY SECTION: Meets first Tuesday alternate months (February-December) in Bakersfield, Calif. *Chairman*, Harry D. Campbell, Franko Western Oil Co., Bakersfield. *Secretary*, W. J. Taylor, Lane-Wells Co., Bakersfield.

SOUTH PLAINS SECTION: Meets third Thursday each month in Lubbock, Tex. *Chairman*, M. C. Gulledge, Magnolia, Brownfield, Tex. *Secretary*, Philip Johnson, Dept. of Petroleum Engineering, Texas Tech., Lubbock.

SOUTHWEST TEXAS SECTION: Meets third Wednesday each month in Corpus Christi: (No meetings in July, August, December.) *Chairman*, Chester L. Wheless, La Gloria Corp. *Secretary*, Robert R. Wallace, Seaboard, Corpus Christi.

WEST CENTRAL TEXAS SECTION: Meets third Wednesday each month in Abilene. *Chairman*, Dalton Moore, Jr., Wimberly Field Unit, Abilene. *Secretary*, Harold Lacik, Warren Petroleum Corp.

WYOMING SECTION: Meets in alternate months in Casper. *Chairman*, M. O. Hegglund, Stanolind Oil & Gas Co., Casper. *Secretary*, R. N. Freeling, Texas Co., Casper.

Drilling Induced Fractures

(Continued from Page 15)

Possible Causes of Induced Fractures

The exact causes of induced fractures are not known. They may be the result of excessive pressures caused by running pipe in the hole. They may be formed while the core is being taken or they may form ahead of the drill bit. The fractures shown in Fig. 1 originated below the top of the core and curve abruptly into the core in a down-the-hole direction. Evidence of fracturing ahead of the bit was obtained in a core of McAlester shale taken near Seminole, Okla. This core included 2 ft cement, 16 ft silty shale, and 5 ft fine-grained, tight Booch sandstone. Neither the cement nor the sandstone were fractured but the shale had a vertical axial fracture with induced fracture characteristics running its entire length. A small step-up caused by chipping of shale away from one side of the fracture and cement forced into the fracture, shown in Fig. 2, reveal that the fracture was present prior to coring.

Importance of Induced Fractures

An economic evaluation of fractured reservoirs necessitates the recognition of induced fractures. Although fractures created in the core during coring are of no economic importance, those produced in the formation adjacent to the well bore may have some importance by increasing transmissability in the immediate vicinity of the hole. Furthermore, general observations show that the physical properties of a rock, such as hardness and brittleness, which favor the development of natural fractures, will also make the rock susceptible to fracture during drilling.

Acknowledgment

The authors are indebted to The Carter Oil Co. and the Standard Oil Co. (New Jersey) for granting permission to publish this paper. ★ ★ ★

Book Reviews

Clay Mineralogy

By Ralph E. Grim. McGraw-Hill Book Co., Inc., New York 1953. 334 p., 9¼ x 6¼ in., bound. $9.00.

The aim of this new text is to summarize available data on the structure, composition, properties, occurrence, and mode of origin of the various clay minerals whose identities have been reasonably well established. The detailed information presented is of importance to engineers, contractors, geologists, oil drillers, the ceramics and paper industries, and many other fields.

Laboratory Instruments

By A. Elliott and J. Home Dickson. Chemical Publishing Co., Inc., New York, 1953. 414 p., 8¾ x 6 in., bound. $7.50.

The chief aim of this book is to provide the research worker with the principles of good design necessary for the construction of instruments in the laboratory workshop. Separate chapters discuss the properties, treatment, and use of various materials; methods of construction to meet special requirements; kinematic design of instruments; sensitivity and distributing influences; the considerable subject of optical instruments and optical glass; and the use of photography in research.

Local Section Officers Get

SOUTHWEST TEXAS LOCAL SECTION

SOUTHWEST TEXAS SECTION OFFICERS AND DIRECTORS set to handle the Petroleum Branch Fall Meeting as well as a full local program are, left to right: Chester Wheless, chairman, La Gloria, Corpus Christi; Don Lewis, director, Crutchfield & Pruett, Corpus Christi; C. N. Carothers, director, Humble, Kingsville; and R. E. Warner, director, Forest Oil Co., San Antonio. Back row, left to right, are: R. C. Hagens, director, Panhandle, Corpus Christi; Ivan Tucker, director, Atlantic, Corpus Christi; Robert R. Wallace, secretary-treasurer, Seaboard, Corpus Christi; Dallas Staples, director, Texas Co., Alice; Houston Parish, director, Engineering Service Co., Inc., Corpus Christi; and Roy Die, director, Humble, Corpus Christi. Not pictured are Robert K. Guthrie, vice-chairman, Seeligson Engineering Committee, San Antonio; and H. F. Adrian, director, Quintana Petroleum Corp., Refugio.

PACIFIC PETROLEUM CHAPTER

PACIFIC PETROLUEM CHAPTER OFFICERS have made plans for an active year. At the planning session were, seated left to right: Kemp E. Barley, councilor, Baroid; M. E. Loy, Chapter chairman, Schlumberger; F. Lowry Wadsworth, retiring chapter chairman, General Petroleum; and John S. Bell, Humble, councilor. Standing are: R. S. Crog, retiring technology chairman, Union Oil Co.; Phil G. Cook, membership chairman, Union Oil Co.; C. R. Dodson, retiring chapter vice-chairman, now of the National City Bank of New York; Harold M. Stanier, councilman, Sunray; Nick van Wingen, senior past chairman, Petroleum Technologists, Inc.; J. A. Klotz, secretary, California Research Corp.; and J. S. Baker, treasurer and councilor, Lane Wells.

PERMIAN BASIN LOCAL SECTION

PERMIAN BASIN SECTION OFFICERS for 1954 are, left to right: J. B. McClellan, secretary-treasurer, Dowell; J. R. Brack, chairman, Ohio Oil Co.; A. L. Carpenter, vice chairman in charge of programs, Humble; and W. L. Grossman, vice-chairman in charge of membership, Halliburton. At the February meeting of this group, E. L. Anders, Jr., spoke on "Sub-surface Conditions of Oil Producing Areas in Texas."

Ready For 1954 Activities

FORT WORTH LOCAL SECTION OFFICERS for 1954 are, front row, left to right: R. P. Roe, fourth vice-chairman, Stanolind; H. A. Metzger, third vice-chairman, Lane-Wells. Back row, left to right, are: M. I. Taylor, chairman, Gulf; L. H. Bond, Jr., first vice-chairman, Fort Worth National Bank; and B. J. Bonner, secretary-treasurer, T&P Coal and Oil Co. Not pictured is G. P. Laflin, second vice-chairman, Dowell. Directors are T. M. Curtis, Stanolind; R. T. Durst, Gruy and Durst; R. W. Erwin, Salt Water Control, Inc.; K. C. Howard, Richardson and Bass; and J. G. Richards, Texas Co.

FORT WORTH LOCAL SECTION

NORTH TEXAS LOCAL SECTION OFFICERS smile over prospects for 1954 and their 53.8 per cent increase in membership in 1953. Left to right, they are: Julian C. Herring, membership chairman, Magnolia; Rollie P. Dobyns, retiring chairman, U. S. Bureau of Mines; John Bolstad, director, Continental; Elmer A. Milz, Section vice-chairman, Shell; David B. Meisenheimer, Section chairman, Texas Co.; Peter F. Chapman, secretary, Shell; Roland Gouldy, program chairman, Hull-Silk Repressuring Assn.; and A. J. Kerr, arrangements chairman, Lane-Wells. Officers not shown in the picture are Kenneth Austin, treasurer; Maynard Stephens, director, Ryder-Scott Co.; and Jack F. Berry, publicity chairman, Texas Co.

NORTH TEXAS LOCAL SECTION

DALLAS LOCAL SECTION LEADERS peruse a business statement as they plan for 1954. Seated, left to right, they are: T. L .Kennerly, program chairman, Core Lab.; Rufus Madera, Section vice-chairman, Republic Natural Gas; Guy R. Brainard, Jr., Section chairman, Lucerne Corp. Standing, left to right, are: Aurel E. Smith, arrangements chairman, British-American; Al B. Dyes, secretary-treasurer, Atlantic; Kenneth W. Robbins, membership chairman, Otis Pressure Control; and Paul Meadows, Journal reporter, U. S. Bureau of Mines. Directors of the Dallas Section are R. T. Bright, Mercantile National Bank, John J. Arps, British-American, and E. G. Trostel, DeGolyer & MacNaughton.

DALLAS LOCAL SECTION

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Proposed for Membership, Petroleum Branch

Total AIME membership on Dec. 31, 1953, was 19,718; in addition 2,195 Student Associates were enrolled.

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INSTITUTE ADMISSIONS COMMITTEE

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The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

In the following list C/S means change of status; R, reinstatement; M, Member; J, Junior Member; A, Associate Member; S, Student Associate.

California

Brea — Brown, James Spencer (M).
Huntington Park — McPhee, William Arthur (J).
Los Angeles — Fernandes, Robert John (C/S-A-M).
Whittier — Cheyney, George Raymond (J).
Wilmington — Savoy, Basil Victor (C/S-J-M).
San Francisco — Fairlie, Philip Galbraith (R, C/S-S-M).

Colorado

Denver — Conaway, Don William (M); Hill, Robert Cowdery, (R, C/S-J-M); Polumbus, Emile Anthony, Jr. (M).

Illinois

Centralia — Slider, Hartzel Clinton (J).
Salem — Wilson, Bruce Lamont (J).

Kansas

Ellinwood — Tiemeier, Paul Arthur (C/S-A-M).

Louisiana

Baton Rouge — Whatley, Errol Reneth, Jr. (J).
Delhi — Fehrmann, Robert Lee (J).
Gretna — Blomquist, Harry Laurentz, Jr. (R, C/S-S-J).
New Orleans — Gaffron, John M. C. (C/S-A-M); Le Blanc, Owen Vincent (M); Tankersley, William Richard (J).
Shreveport — Bean, Ernest F., Jr (C/S-A-M); Cook, John Grady (J); Rogers, Robert Errett (M).

Massachusetts

Amherst — Farrington, William Benford (M).

Mississippi

Jackson — Knobloch, Guy Joseph (M).
Natchez — McEver, Billy J. (J).

Montana

Lewiston — Bush, Herbert Howard (C/S-A-M).
Billings — Mullen, John Timothy, Jr. (R, M).

Oklahoma

Norman — Melton, Frank A. (M).
Oklahoma City — Powell, Herbert Edward (M); Young, Elburn Eugene (R, C/S-S-M); Heath, John Lester, Jr., (R, C/S-S-M).
Tulsa — Bourne, Benjamin William (M); Crews, William Daryl (J); Gregath, James Reed (J); Lembcke, Richard Edward (M); Merliss, Frederick E. (J); Smith, Loyd Thompson (M).

Texas

Abilene — Cannon, Cecil Nathaniel (M); McGarr, Howell Joe (M).
Corpus Christi — Gill, William Gillette (M); Laws, James Taylor (J).
Dallas — Johnston, Orville Charles (M); Lewelling, Henry (R, M); Quayle, Alexander (M); Stepp, Vern E. (R, M).
Fort Worth — Netherland, Clarence Martin (M).
Houston — Holden, James Edward (J); Murray, John Rylen (C/S-A-M); White, Alvin Vernon (R, C/S-S-M); McCarty, Dana Gerald (C/S-A-M).
Kilgore — Van Os, Seymour, Jr. (M).
Levelland — Jones, Charles William (M).
McAllen — David, James Marion (J).
Midland — Anderson, Eldon Dean (M); Swaim, Howard Winston (C/S-A-M).
Odessa — Franks, Bennie Louis (R, C/S-S-J).
Overton — Garrot, Floyd Elmo (J); Lucy, Marius James (J); Sullivan, Bruce Millen (M).
Pickton — Wheeler, Frank Warren (J).

Washington

Shelton — Crosby, Hartzell Lance (M).

Wyoming

Baroil — Lannan, John Casimir (J).
Casper — Curtis, Lawrence Buck (J); Redwine, Fletcher Horton (J).
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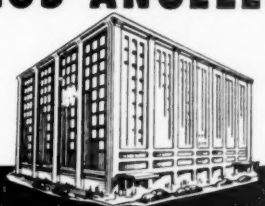

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COMPANIES OFFER GRADUATE FELLOWSHIPS IN 1954-55 TO UNIVERSITY OF OKLAHOMA

Five graduate fellowships in the School of Petroleum Engineering at the University of Oklahoma are available for the academic year 1954-55. Humble, Lane Wells, Shell, Sinclair, and Stanolind are offering the fellowships.

The stipends offered by the companies range from 1,200 to 1,600 per academic year, plus additional sums for tuition, fees, and purchase of special equipment ranging from $300 to $1,000, according to the fellowship offer.

The holder of each of the fellowships will be a candidate for the master's degree in petroleum engineering. The Stanolind fellowship specifies training in the displacement of oil from reservoir material; the Sinclair fellowship is for study in secondary recovery; and the Lane Wells fellowship is for study in the field of well completions. Humble and Shell give no specification as to field of study.

The closing date for applications to be received by H. W. Benischek, chairman of the School of Petroleum Engineering, is Apr. 15, 1954. Applications are invited from men having bachelor's degrees in petroleum engineering or a related field from any accredited school.

Original applications should give full particulars concerning: name, age, place of birth, citizenship, marital status, complete record of college or university training (including manuscripts), three letters of recommendation, status under the G.I. Bill of Rights, extra curricular activities, attainment in industrial experience, and other pertinent details.

Engineering Manpower Commission of EJC Has Three AIME Members

Three AIME members are on the Engineering Manpower Commission of the Engineers Joint Council. They are: George B. Corless, Standard Oil Co. (N. J.), Harold K. Work, College of Engineering, New York University, and Lyman H. Hart, American Smelting and Refining Co.

The Commission for the past four years has been concerned with "the relationship of specialized manpower to our overall mobilization structure."

AIME Student Paper Contest Adds Sixth Award of $100

An additional award of $100 for graduate students in the AIME National Student Prize Paper Contest has been authorized. Hereafter, winners in local section contests will have six chances instead of five to win further honors.

Three undergraduates and three graduate student prizes of $100 will be awarded. One prize in each group will be given to students in Mining, Metals, and Petroleum, provided papers of a sufficiently high caliber are entered.

Junior Members will be eligible to compete as well as Student Associates, if they are doing at least half of their work in preparation for a master's degree.

James Milo Stewart, Student Associate at the University of Kansas, now in the U. S. Navy, is one of the winners of the 1953 contest. His paper is "Calculation of Gas Reserves in a Small Kansas Gas Pool," entered by the Kansas Section. No graduate papers of sufficiently high standard were entered this year from any branch.

FREE TO AIME MEMBERS

Production Review Summary For 1953

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28 PAGES

A COMPLETE, INTERPRETATIVE REVIEW OF LAST YEAR'S PRODUCTION HIGHLIGHTS PREPARED FROM FINAL STATISTICS RELEASED BY MAJOR COMPANIES AND GOVERNMENTS.

Prepared by the Petroleum Branch, AIME Production Review Committee and presented at the Annual AIME Meeting in New York.

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DRILLING INFORMATION EXCHANGE EXPLAINED

An exchange of drilling information and experience which has been taking place in the Rocky Mountain region for the last two and one-half years was explained by E. A. Polumbus, Jr., in a recent talk before the Denver Local Section.

"Some General Aspects of Drilling Characteristics and Control in the Rocky Mountain Region" was the title of the address by the Denver petroleum engineer.

He explained that accelerated drilling activity and continuing rise in the cost of finding oil is presenting a challenge to operators and drilling contractors to intensify their search for more efficient and less expensive methods of drilling for oil.

In the Rocky Mountain Region, drilling activity has increased over 300 per cent during the past five years. During 1953, more than 17 million feet of hole was drilled in wildcat and development wells.

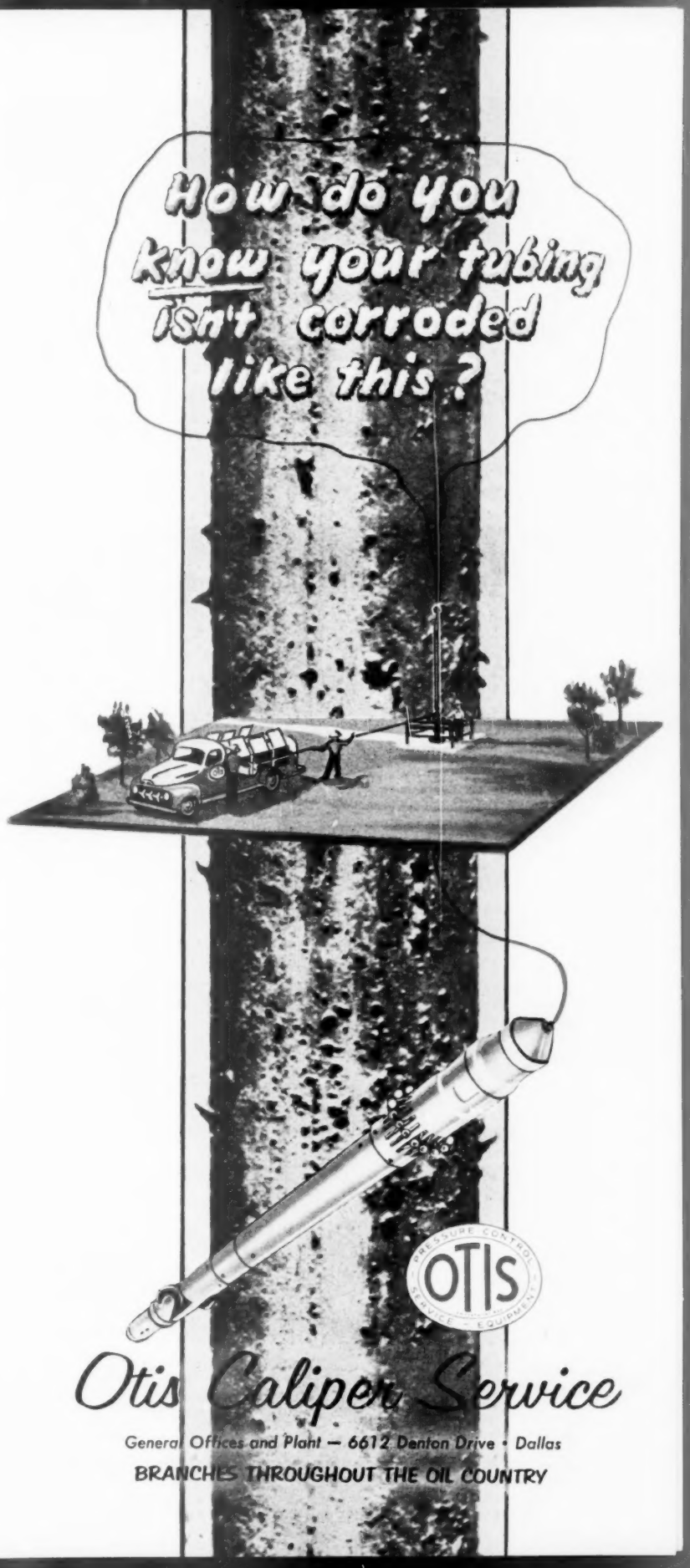
Recognizing this challenge, Polumbus' engineering group inaugurated a Drilling Analysis Service about two and one-half years ago. Basically the service provides for the exchange of drilling experiences in an orderly and systematic manner. This allows the industry of that area, rather than individuals, to review the varied experiences and, where possible, effect improvements.

In the service, wells are selected for analysis to: (1) evaluate special drilling techniques and problems, (2) evaluate benefits of diamond drilling, (3) study improvement in drilling progress in active development areas, and (4) compare slim-hole drilling with conventional drilling.

Slides were presented to show how how the analyses can be used to study penetration characteristics of various formations at various depths. Statistical correlations were presented relating new hole bits to net days in various basins.

A statistical correlation was shown in which normal time per round trip with drill pipe was related to depth. It was pointed out how this correlation is particularly useful in estimating net drilling time in a given area where only "on bottom" time is available.

The speaker explained that the purpose of his talk was to stimulate interest in the importance of better understanding of drilling characteristics and control in the Rocky Mountain area by showing examples of techniques in drilling efficiency. ★★★



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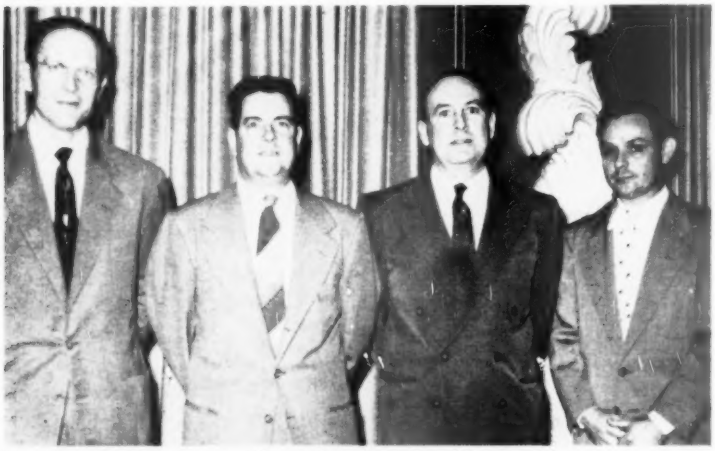
BRANCHES THROUGHOUT THE OIL COUNTRY

SOUTH PLAINS LOCAL SECTION meeting. Left to right are: Norman Lamont, Texas Tech; B. J. Rhoades (the speaker), Odex; J. J. Riha, Stanolind; K. D. McPeters, Stanolind; William H. Waddlington, Stanolind; and John Sanders, Magnolia.



THE LOU-ARK SECTION officers for 1954 are, left to right: E. S. Doyle, second vice-chairman, First National Bank of Shreveport; E. P. Ogier, secretary-treasurer, W. C. Spooner, Inc.; B. F. Patterson, Jr., first vice-chairman, The Texas Co.; and C. R. Olson, chairman, Ohio Oil Co.

NEW OFFICERS OF THE WEST CENTRAL TEXAS SECTION are, left to right: James E. Russell, second vice-chairman, Reddin Operators Committee; Dalton Moore, Jr., chairman, Wimberly Field Unit; and Harold Lacik, secretary-treasurer, Warren Petroleum Corp. Not pictured is Joe B. Jenkins, first vice-chairman, Stanolind.

Tulsa Study Group Hears Talk on Unitizing Early

Alvin E. Hall, an area supervising petroleum enginer for Phillips Petroleum Co., spoke to the Mid-Continent Study Group recently on the unitizing of an oil field early in its life.

Information was presented concerning the Southwest Antioch Gibson Sand unit, located in Garvin County, Okla., which was unitized before the bottom-hole pressure had undergone a severe decline.

Four months after the field was unitized on Apr. 1, 1948, gas injection facilities were in operation and produced gas was returned to the reservoir. Gas injection early in the life of the field resulted in maintaining higher rates of production than in the adjacent, non-unitized fields, he explained.

The original unit of 67 wells has been enlarged five times under the Oklahoma unitization law, and now contains 238 wells on 9520 acres. Participation in the unit is based on a formula which contains the following factors. Acre-feet of productive sand, bottom-hole pressure, well potential, and rate of oil production at a specified maximum daily gas production.

As a result of water injection, the gas-oil ratio has been maintained approximately constant and the rate of oil production has been maintained at approximately 6500 B/D for the past 18 months. Oil production is increasing gradually and at the present time the unit is producing 7000 B/D.

AIME-Socony Vacuum Offer Scholarship; Rules Revised

The AIME-Socony-Vacuum Scholarship of $750 for undergraduates in petroleum engineering or allied curricula is being offered again in 1954-55, according to Jack I. Laudermilk, Socony Vacuum Oil Co. Revised rules for the award will be announced later.

The scholarship will be administered by a committee of six, to include: three members of the Petroleum Branch, the executive secretary of the Branch as chairman, the present secretary of the Technical Publications Committee as secretary, and the secretary of the Student Relations Committee of the Institute, ex officio.

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to positions coded Y9664, C1605A and Y9516 below should be addressed to Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

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♦University Position. Teacher qualified for courses in reservoir mechanics and reservoir engineering on the advanced undergraduate level. Should have an advanced degree, although not necessarily in petroleum engineering. Rank and salary are open. Division of Petroleum and Natural Gas Engineering, The Pennsylvania State University, State College, Pa.

♦Petroleum Engineer. Britian with seven years experience with major company in drilling, production, and subsurface engineering in different parts of the world desires position in California. Code 213.

♦Geologist, PhD with minors in geophysics and petroleum engineering; undergraduate engineering mathematics. Experience as collegiate mathematics instructor and in principal phases of exploration in major petroleum provinces. Desires position in reservoir engineering or evaluation work. Available about April 15. Code 214.

POSITIONS

♦A state university in a major oil producing state in the South is expanding its petroleum engineering department. If you are interested in teaching and research and have an advanced degree in engineering or science with company experience, you should investigate this opportunity. Please submit complete resume. Code 557.

♦Oil Field Production Assistant with experience keeping field records, tabulating data and typing reports. Salary, $3900-$5200 a year. Headquarters, New York, N.Y., Y9664.

♦Sales Engineering Trainee, 25-29, engineering degree. Must have been an honor student and have definite sales aptitude. Will sell complete lubricating program to industrials covering full line of petroleum products, and will deal with top management for most part. Salary $400-$450 per month. Employer will negotiate fee. Location, Chicago. C1605A.

♦Senior Design Engineer with petroleum refinery experience, to take charge of plant design, layout and liaison work with oil company. Salary, $8000 a year. Location, New York, N.Y. Y9516.

Fracture Treatments Talk Given to Dallas Section

"Evaluation of Fracture Treatments" was the subject of a talk by E. H. Timmerman, Shell Oil Co., before 90 members of the Dallas Local Section in February.

The value of pressure build-up data studies following fracture treatments was explained by Timmerman, Tulsa area reservoir engineer for Shell. Fracture treatments overcame detrimental effects of drilling and completing operations in cases pointed out by the speaker.

The calculated detrimental effects, or skins, and the productivity indices both indicated that fracture treatments reduced pressure drop when measured with the well flowing at a common rate in the wells cited. Timmerman said that the build-up method alone can be used to forecast the results of fracture treatments as well as to study the effectiveness of various completion practices.

He stated, "Fracture treatments can be expected to prolong the flowing life of these wells and some increase in ultimate recovery may be anticipated.

HAVE YOU CHANGED YOUR ADDRESS?

In order that publications and correspondence may reach you promptly, the Petroleum Branch, AIME, should be advised as soon as possible of any change in your address, *preferably a month before the change becomes effective.* For the AIME directory and for the Personals column of the JOURNAL OF PETROLEUM TECHNOLOGY, additional information is desired. The form below is provided for your convenience, and should be sent to Petroleum Branch, AIME, 800 Fidelity Union Bldg., Dallas 1, Tex.

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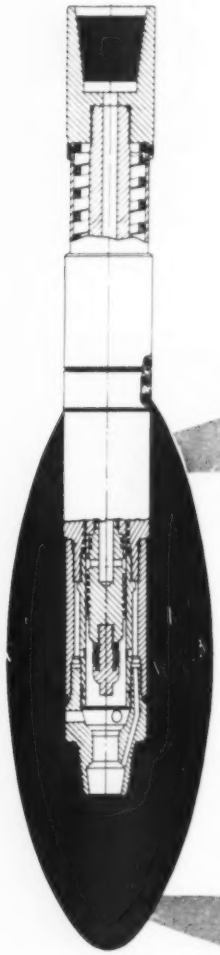

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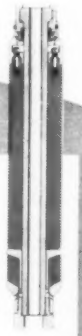

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Reports on Germany, Local Production Heard by Pacific Chapter Junior Group

"The Oil Industry in Germany" was the subject of a talk by Bob Pearce, Signal Oil and Gas Co., before the AIME Junior Group of the Pacific Petroleum Chapter at their February meeting. Slides were shown of operations in the Hanover and Emsland areas.

Germany's first discover was near Hanover, in 1874. Including the discovery well, which still produces, 308 wells are now producing 540 B/D of 18-27 gravity oil from the Cretaceous at 300 to 1000 ft. About 17,000,000 bbls have been produced.

Production is also obtained from mines near Hanover. Vertical shafts are dug to the 300-ft level, where oil sand is mined along horizontal beds, removed by rail and elevator, and finally "steam cleaned" at the surface. Recoveries of 1 bbl/ton (about 2000 bbls/acre ft) are obtained in this way. Before a mine is abandoned all cleaned sand is transported back to the mine to prevent future subsidence.

In the Emsland area, which is on the Dutch border west of Hanover, it was not until 1938 that oil was discovered. Soon afterward Germany was at war, heightening the need for oil, and Emsland oil development skyrocketed. However, canals were the only available means of transportation, and by the end of the war, great stores of oil were left at the docks.

By 1947, the U. S. allocated money for reviving the German oil industry, and since then additional production, transportation, and refining capacity has been added.

Germany's total yearly production amounts to about 12,800,000 bbls at the present time, of which 42 per cent comes from the Emsland area. The present 268,000,000 bbl proven reserve is expected to continue its accelerated rise, due principally to development along the Dutch border.

Germany now is able to refine about twice their productive capacity, but consumption exceeds their production by nearly three times. Therefore, in spite of present strides in oil development, it may be some time before the German oil industry can supply its own needs, the speaker stated.

During the remainder of the meeting, a series of brief talks were given on recent activities of the major oil companies.

David K. Hayward, Texas Co., gave a review of drilling and operating problems in the newly discovered Del Amo and Olive fields. Early difficulties with lost circulation were overcome by running more surface pipe and by a particular program of mud control. Gravel packs and heater-treaters have answered certain production problems.

Floyd Schoonover, Monterey Oil Co., spoke of his company's offshore activities at Seal Beach and West Newport Beach. In each area, a discovery well has been completed. At West Newport Beach, where the second well is now being drilled, "frog-men" equipped with aqua lungs have been doing geologic "surface" mapping at 150-200 ft depths, along the ocean floor. The next well at Seal Beach is due to be spudded about Apr. 1, and is to be a straight hole from the steel and concrete drilling island, which is 75 ft in diameter and is located 8000 ft offshore.

Max Taves, Richfield Oil Corp., drew a cross-section through the Wheeler Ridge oil field and located the newly discovered Eocene pool, below and to the north of the thrust fault. Formerly, principal production had been from the Valv, Olcese, and Vedder sands. Now, Eocene wells on 20-acre spacing make over 200 B/D each from the 310-ft sand section.

Harry Keegan, Union Oil Co., described operational features of the Dominguez waterflood. At present 5,000 to 6,000 B/D of oil field brine are injected at wellhead pressures varying between a vacuum and 1950 psi. Surface installations consist of a primary skim pond, an iodine recovery plant, chlorination facilities, an oil-water storage plant, a leaf type filter with filter aid and pre-coat, a clean water storage pit, a centrifugal charging pump, a Triplex fluid injection pump with aluminum bronze fluid end, and cement lined steel pipe leading to injection wells. The large scale water flood project with Union Oil Co., Shell Oil Co., and Dominguez Oil Fields Co. is scheduled to start in midsummer of 1954. ★★★

Necrology

Date Elected	Name	Date of Death
1945	Dana D. Champion	Nov. 7, 1953
1944	Leonard J. Neuman	Dec 18, 1953

Major Membership Drive Starts This Month With 3000 on Mailing List

A major drive for Petroleum Branch AIME membership will be launched this month. Explanations of the benefits of membership will be sent to over 3000 prospective members.

Several mailing pieces are being devised for this membership drive, and three copies of the JOURNAL OF PETROLEUM TECHNOLOGY will be sent to the selected group. The number of new members brought in through this program is expected to surpass the total of almost 700 who joined the Petroleum Branch of the AIME in 1953.

The success of the drive will be dependent upon the work of the local sections in following up the mail approach, says Gene Scheirman, chairman of the Membership Committee for 1954 .

"We hope that each man on our mailing list will be contacted by the local section of his area, and that additional names will be submitted by all sections to the Dallas office," states Scheirman. "Names of the men in each area who are receiving the literature will be sent to the appropriate local section so they may be contacted on a personal basis."

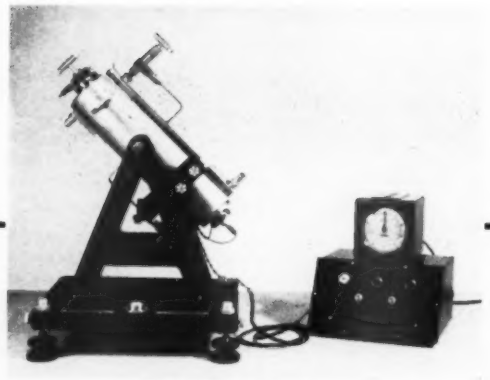
CLAY-WATER SYSTEM CONFERENCE SCHEDULES PETROLEUM PAPERS

The clay-water system will be the subject of the 1954 Pacific Coast Regional Conference on Clays and Clay Technology. The conference is to be held on the Berkley campus of the University of California on June 25 and 26.

Workers in the fields of petroleum, soil science, soil mechanics, geophysics and ceramics will present papers. Permeability of liquids through formations, swelling of clays, viscosity, and plasticity will be the subjects of the papers. Papers will be presented in the morning and discussions will be held in the afternoon.

N. G. GUIBERSON DIES

Nathaniel Greene Guiberson, vice-president and director of The Guiberson Corp., Dallas, and pioneer oil man, died unexpectedly Feb. 15. He founded The Guiberson Corp. in 1919.



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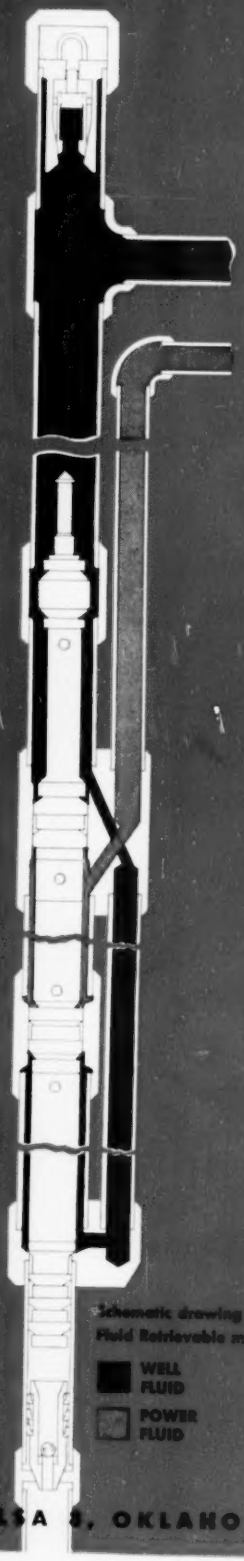

Schematic drawing of Fluid Retrievable model

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